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User's Guide: Computer Program for Simulation of Construction Sequence for Stiff Wall Systems with Multiple Levels of Anchors (CMULTIANC)

William P. Dawkins, Ralph W. Strom, Robert M. Ebeling

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ABSTRACT: This report describes the PC-based computer program CMULTIANC, used to evaluate the effects of staged construction activities (i.e., excavation and tieback post-tensioning) on wall and soil behavior. The CMULTIANC simplified construction sequencing analysis is applicable to stiff walls with a single row or multiple rows of post-tensioned tieback anchors. Top-down construction is assumed in this analysis procedure.

The retaining wall system is modeled using beam on inelastic foundation methods with elastoplastic soil-pressure deformation curves (R-y curves) used to represent the soil behavior. The R-y curves are developed within the CMULTIANC program in accordance with the reference deflection method. The retaining wall is analyzed on a per-unit length run of wall basis. One-dimensional finite elements are used to model the retaining wall with closely spaced inelastic concentrated springs to represent soil-to-structure interactions on both sides of the wall. Discrete concentrated, elastoplastic springs are used to represent the anchors.

For each level of excavation (associated with a particular tieback installation) CMULTIANC performs three sequential analyses: (a) staged excavation analysis (to the excavation level needed for anchor installation) to capture soil loading effects, (b) R-y curve shifting to capture plastic soil movement effects, and (c) tieback installation analysis to capture tieback anchor prestressing effects. R-y curves are shifted to capture the plastic movement that takes place in the soils as the wall displaces toward the excavation for those conditions where actual wall computed displacements exceed active computed displacements. R-y curve shifting is necessary to properly capture soil reloading effects as tieback anchors are post-tensioned and the wall is pulled back into the retained soil.

Contents

List of Figures

List of Tables

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units using the following factors.

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
kip-feet	1,355.8181	newton-meters
kips per square foot	47.88026	kilopascals
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square inches	0.00064516	square meters
tons per square foot	9,764.856	kilograms per square meter

Preface

This report describes the software program CMULTIANC, newly developed to simulate the simplified construction sequence method of analysis of a stiff, tieback wall with multiple levels of prestressed anchors (assuming top-down construction). Funding for this research was provided by the Computer-Aided Structural Engineering Research Program sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Infrastructure Technology Research and Development Program. Ms. Yazmin Seda-Sanabria, Geotechnical and Structures Laboratory (GSL), Vicksburg, MS, U.S. Army Engineer Research and Development Center (ERDC), was Program Manager. The study was conducted under Work Unit 31589, "Computer-Aided Structural Engineering (CASE)," for which Dr. Robert L. Hall, GSL, is Problem Area Leader and Mr. Chris Merrill, Chief, Computational Science and Engineering Branch, Information Technology Laboratory (ITL), ERDC, is Principal Investigator. The HQUSACE Technical Monitor is Ms. Anjana Chudgar, CECW-ED.

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Commander and Executive Director of ERDC was COL John W. Morris III, EN. Director was Dr. James R. Houston.

1 Background on Tieback Retaining Wall Systems

This report describes the personal computer (PC) -based computer program CMULTIANC, used to simulate the simplified construction sequence method of analysis of a stiff tieback wall. Top-down construction is assumed in this analysis procedure.

The user's guide to CMULTIANC is given in Chapter 2. This chapter serves as an introduction to the categorization and analysis of "flexible" and "stiff" tie-back retaining wall systems involving the use of prestressed anchors. The multi-anchored tieback earth retaining wall systems used by the U.S. Army Corps of Engineers are classified as either "flexible" or "rigid" according to Strom and Ebeling (2001, 2002) and Ebeling et al. (2002). The categorization of a tieback wall as being either flexible or rigid is used for convenience in determining the appropriate analysis and/or design procedure associated with a particular type (i.e., category) of wall.

1.1 Design of Flexible Tieback Wall Systems

The equivalent beam on rigid support method of analysis using apparent earth-pressure envelopes is most often the design method of choice, primarily because of its expediency in the practical design of tieback wall systems. This method provides the most reliable solution for ***flexible*** wall systems, i.e., soldier beam-lagging systems and sheet-pile wall systems, since for these types of systems a significant redistribution of earth pressures occurs behind the wall. Soil arching, stressing of ground anchors, construction-sequencing effects, and lagging flexibility all cause the earth pressures behind flexible walls to redistribute to, and concentrate at, anchor support locations (FHWA-RD-98-066). This redistribution effect in flexible wall systems cannot be captured by equivalent beam on rigid support methods or by beam on inelastic foundation analysis methods where the active and passive limit states are defined in terms of Rankine or Coulomb coefficients. Full-scale wall tests on flexible wall systems (FHWA-RD-98-066) indicated that the active earth pressure used to define the minimum load associated with the soil springs behind the wall had to be reduced by 50 percent to match measured behavior. Since the apparent earth-pressure diagrams used in equivalent beam on rigid support analyses were developed from measured loads, and thus include the effects of soil arching, stressing of ground anchors, construction-sequencing effects, and lagging flexibility, they provide a better indication of the strength performance of flexible tieback wall systems. This is not the case for ***stiff*** wall systems, however, and in fact the diagrams are applicable only to those flexible wall systems in which

- Overexcavation to facilitate ground anchor installation does not occur.
- Ground anchor preloading is compatible with active limit state conditions.
- The water table is below the base of the wall.

The design of flexible wall systems is illustrated in Ebeling et al. (2002).

1.2 Design of Stiff Tieback Wall Systems

Construction-sequencing analyses are important in the evaluation of stiff tieback wall systems, since for such systems the temporary construction stages are often more demanding than the final permanent loading condition (Kerr and Tamaro 1990). This may also be true for flexible wall systems where significant overexcavation occurs and for flexible wall systems subject to anchor prestress loads producing soil pressures in excess of active limit state conditions. The purpose of the example problems contained herein is to illustrate the use of construction-sequencing analysis for the design of stiff tieback wall systems. Although many types of construction-sequencing analyses have been used in the design of tieback wall systems, only three types of construction-sequencing analyses are demonstrated in the example problems. The three construction-sequencing analyses chosen for the example problems are ones considered to be the most promising for the design and evaluation of Corps tieback wall systems:

- Equivalent beam on rigid supports by classical methods (identified as the RIGID 2 method by Strom and Ebeling 2002).
- Beam on inelastic foundation methods using elastoplastic soil-pressure deformation curves (R-y curves) that account for plastic (nonrecoverable) movements (identified as the WINKLER 1 method by Strom and Ebeling 2002).
- Beam on inelastic foundation methods using elastoplastic soil-pressure deformation curves (R-y curves) for the resisting side only with classical soil pressures applied on the driving side (identified as the WINKLER 2 method by Strom and Ebeling 2002).

The results from these three construction-sequencing methods are compared in Strom and Ebeling (2002) with the results obtained from the equivalent beam on rigid support method using apparent pressure loading (identified herein as the RIGID 1 method). Recall that apparent earth pressures are an envelope of maximum past pressures encountered over all stages of excavation. The results are also compared with field measurements and finite element analyses in Strom and Ebeling (2002).

1.2.1 Identifying stiff wall systems

Five focus wall systems were identified and described in detail in Strom and Ebeling (2001):

- Vertical sheet-pile system with wales and post-tensioned tieback anchors.
- Soldier beam system with wood or reinforced concrete lagging and post-tensioned tieback anchors. For the wood lagging system, a permanent concrete facing system is required.
- Secant cylinder pile system with post-tensioned tieback anchors.
- Continuous reinforced concrete slurry wall system with post-tensioned tieback anchors.
- Discrete concrete slurry wall system (soldier beams with concrete lagging) with post-tensioned tieback anchors.

Deformations and wall movements in excavations are a function of soil strength and wall stiffness, with wall stiffness a function of structural rigidity EI of the wall and the vertical spacing of anchors L. Soil stiffness correlates to soil strength; therefore, soil strength is often used in lieu of soil stiffness to characterize the influence of the soil on wall displacements. Steel sheet-pile and steel soldier beams with timber lagging systems are considered to be flexible tieback wall systems. Secant cylinder pile, continuous concrete slurry wall, and discrete concrete slurry wall systems are considered to be stiff tieback wall systems. The effect of wall stiffness on wall displacements and earth pressures is described in Xanthakos (1991) and in FHWA-RD-81-150. In the FHWA report, it is indicated that Clough and Tsui (1974) showed, by finite element analyses, that wall and soil movements could be reduced by increasing wall rigidity and tieback stiffness. None of the reductions in movements were proportional to the increased stiffness, however. For example, an increase in wall rigidity of 32 times reduced the movements by a factor of 2. Likewise, an increase in the tieback stiffness by a factor of 10 caused a 50 percent reduction in movements.

Other investigators have also studied the effect of support stiffness for clays (as reported in FHWA-RD-75-128). They defined system stiffness by EI/L^4, where EI is the stiffness of the wall and L is the distance between supports (Figure 1-1). The measure of wall stiffness is defined as a variation on the inverse of Rowe's flexibility number for walls, and is thus expressed by EI/L^4, where L is the vertical distance between two rows of anchors. Wall stiffness refers not only to the structural rigidity derived from the elastic modulus and the moment of inertia, but also to the vertical spacing of supports (in this case anchors). It is suggested by Figure 9-106 in FHWA-RD-75-128 that, for stiff clays with a stability number $\gamma H/s_u$ equal to or less than 3, a system stiffness EI/L^4 of 10 or more would keep soil displacement equal to or less than 1 in.[1,2] However, other factors, such as prestress level, overexcavation, and factors of

[1] At this time, the authors of this report recommend that, when tieback wall system displacements are the quantity of interest (i.e., stringent displacement control design), they should be estimated by nonlinear finite element-soil structure interaction (NLFEM) analysis.

[2] A table of factors for converting non-SI units of measurement to SI units is presented on page vii.

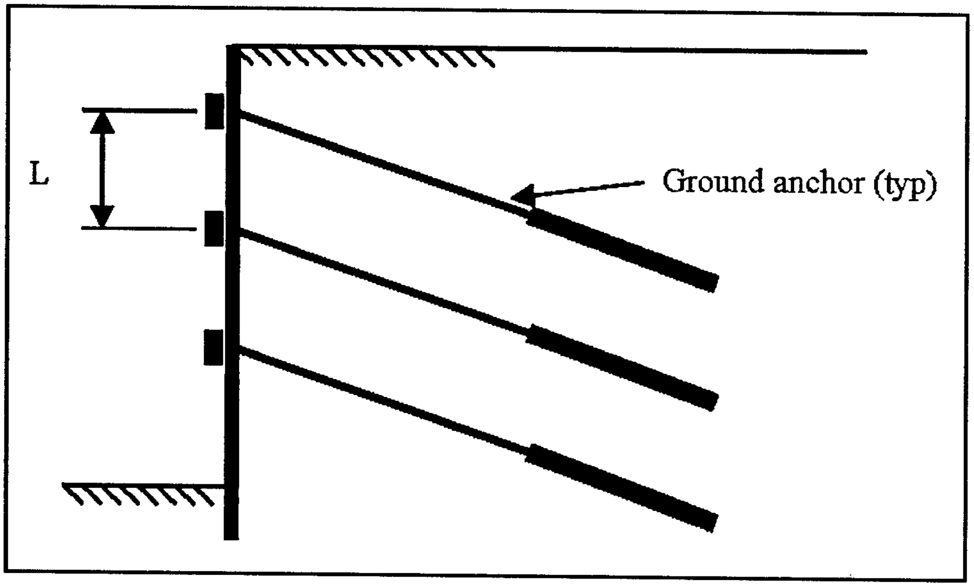


Figure 1-1. Definition of span length *L*

safety, also influence displacement. Data in this figure clearly indicate that stiff wall systems in stiff clays will displace less than flexible wall systems in soft clays. Table 1-1 categorizes flexible and stiff wall systems with respect to the focus wall systems of the Strom and Ebeling (2001) report.

Table 1-1
Stiffness Categorization of Focus Wall Systems (Strom and Ebeling 2001)

Focus Tieback Wall System Description	Wall Stiffness Category	
	Flexible	*Stiff*
Vertical sheet-pile system	√	
Soldier beam system	√	
Secant cylinder pile		√
Continuous reinforced concrete slurry wall system		√
Discrete concrete slurry wall system		√

Using the approach of FHWA-RD-75-128, the wall stiffness can be quantified in terms of the flexural stiffness EI per foot run of wall and in terms of the relative flexural stiffness EI/L^4. This information is presented in Table 1-2 for the focus wall systems of the Strom and Ebeling (2001) report. The relative flexural stiffness in the table is based on a span length L, i.e., a vertical anchor spacing of 10 ft.

It should be recognized from these stiffness calculations that a secant pile system with L equal to 28.5 ft would produce a flexural stiffness value of EI/L^4 equal to that for the vertical sheet-pile wall system with L equal to 10 ft. Therefore, it is possible, by spacing anchors at close intervals, to obtain a stiff wall system using flexible sheetpiling or, vice versa, to obtain a flexible wall system using secant piles with widely spaced anchors.

Table 1-2
General Stiffness Quantification for Focus Wall Systems (Strom and Ebeling 2001)

Wall Stiffness	Wall System	EI k-ft²/ft × 10⁴	EI/L^4 ksf/ft
Flexible	Vertical sheet-pile system	0.3 to 5.0	3.7 [1]
	Soldier beam system	0.1 to 4.0	1.5 [2]
Stiff	Secant cylinder pile	8.0 to 250.0	239.8 [3]
	Continuous reinforced concrete slurry wall	30.0 to 150.0	123.1 [4]
	Discrete concrete slurry wall	35.0 to 160.0	92.3 [5]

[1] Relative stiffness based on PZ 27 sheetpiling. Per Olmsted Prototype Wall.
[2] Relative stiffness based on HP12×53 soldier beams spaced at 8.0 ft on center (OC). Per FHWA-RD-97-130 design example.
[3] Relative stiffness based on 5.0-ft-diam caisson piles spaced at 7.0 ft OC. Per Monongahela River Locks and Dams 2 Project.
[4] Relative stiffness based on 3.0-ft-thick continuous slurry trench wall. Per Bonneville Navigation Lock temporary tieback wall.
[5] Relative stiffness based on W36 × 393 soldier beams spaced at 6.0 ft OC with concrete lagging. Per Bonneville Navigation Lock upstream wall.

1.2.2 Tieback wall performance objectives

1.2.2.1 Safety with economy design. Common factors of safety used in practice for the design of anchored walls range between 1.1 and 1.5 applied to the shear strength of the soil and used in the calculation of the earth-pressure coefficient that characterizes the magnitude of the total force applied to the wall (FHWA-RD-98-065). Values adopted for a factor of safety vary with the importance of the wall, the consequences of failure, the performance objective (i.e., "safety with economy" or "stringent displacement control"), and economics. (Ebeling et al. 2002 and Strom and Ebeling 2002 adopted this terminology for engineering procedures used in the design of flexible and stiff tieback walls.)

Factors of safety ranging from 1.1 to 1.2 are generally considered unacceptable for the design of permanent walls. Walls constructed with factors of safety between 1.1 and 1.2 may be stable, but may also experience undesirable displacements near the wall (FHWA-RD-98-065). Therefore, factors of safety in this range should be used with caution and only for temporary walls where large displacements are considered to be acceptable. The design and construction of a temporary excavation tieback wall support system with a low factor of safety (i.e., large displacements were anticipated) is described in Cacoilo et al. (1998). For permanent walls, in most situations some lateral movement of the tieback wall system can be tolerated, recognizing that with lateral wall movement, settlements will occur in the retained soil immediately behind the wall. Tieback wall designs based on strength only, without special consideration of wall displacement, are termed safety with economy designs.

The Soletanche wall example (discussed in Chapter 2 of Strom and Ebeling 2002) is a safety with economy design. This means that, for flexible wall systems, the tieback anchors and wall system can be designed for soil pressure conditions approaching active state conditions. As such, the apparent earth pressure diagrams used in the design can be based on a total load approach using a factor of safety of 1.3 applied to the shear strength of the soil per the design recommendations of FHWA-RD-97-130. Trapezoidal earth pressure distributions are used for this type of analysis. For stiff wall systems, active earth pressures in the retained soil can often be assumed and used in a construction-sequencing analysis to size anchors and determine wall properties. Earth pressure distribution for this type of analysis would be in accordance with classical earth pressures theory, i.e., triangular with the absence of a water table.

The general practice for the safety with economy design is to keep anchor prestress loads to a minimum consistent with active, or near-active, soil pressure conditions (depending upon the value assigned to the factor of safety). This means the anchor size would be smaller, the anchor spacing larger, and the anchor prestress lower than those found in designs requiring "stringent displacement control."

1.2.2.2 "Stringent displacement control" design. A performance objective for a tieback wall can be to restrict wall and soil movements during excavation to a tolerable level so that structures adjacent to the excavation will not experience distress (as for the Bonneville temporary tieback wall example). According to FHWA-RD-81-150, the tolerable ground surface settlement may be less than 0.5 in. if a settlement-sensitive structure is founded on the same soil used for supporting the anchors. Tieback wall designs that are required to meet specified displacement control performance objectives are termed stringent displacement control designs. Selection of the appropriate design pressure diagram for determining anchor prestress loading depends on the level of wall and soil movement that can be tolerated. Walls built with factors of safety between 1.3 and 1.5 applied to the shear strength of the soil may result in smaller displacements if stiff wall components are used (FHWA-RD-98-065).

To minimize the outward movement, the design would proceed using soil pressures at a magnitude approaching at-rest pressure conditions (i.e., a factor of safety of 1.5 applied to the shear strength of the soil). It should be recognized that even though the use of a factor of safety equal to 1.5 is consistent with an at-rest (i.e., zero soil-displacement condition) earth pressure coefficient (as shown in Figure 3-6 of Engineer Manual 1110-2-2502 (Headquarters, U.S. Army Corps of Engineers 1989)), several types of lateral wall movement could still occur. These include cantilever movements associated with installation of the first anchor; elastic elongation of the tendon anchor associated with a load increase; anchor yielding, creep, and load redistribution in the anchor bond zone; and mass movements behind the ground anchors (FHWA-SA-99-015). It also should be recognized that a stiff rather than flexible wall system may be required to reduce bending displacements in the wall to levels consistent with the performance objectives established for the stringent displacement control design. A stringent displacement control design for a flexible wall system, however, would result in anchor spacings that are closer and anchor prestress levels that are higher than those for a comparable safety with economy design. If displacement control is a critical performance objective for the project being designed, the use of a stiff rather than flexible wall system should be considered.

1.2.3 Progressive design of tieback wall systems

As with most designs, a progressive analysis (starting with the simplest design tools and progressing to more comprehensive design tools when necessary) is highly recommended by the authors. With respect to flexible wall systems, some of the more comprehensive analysis tools used for stiff wall system analysis (construction-sequencing analysis based on classical earth pressure distributions and beam on inelastic foundation analysis) are not generally considered appropriate for the analysis of flexible wall systems. This is because apparent pressure diagrams, since they are "envelopes" based on measurements made during construction, include the effects of soil arching, wall flexibility, preloading of supports, facial stiffness, and construction sequencing. However, with stiff wall systems, these items will not affect earth pressure redistribution to the same extent they affect flexible wall systems. Therefore, in practice, construction-sequencing analyses and beam on inelastic foundation analyses are considered valid tools for the investigation of stiff wall system behavior. The design and analysis tools typically used in the design and analysis of flexible and stiff wall systems are summarized in Tables 1-3 and 1-4, respectively, starting with the simplest design tool and progressing to the more comprehensive analytical tools. The most comprehensive design tools are linear elastic finite element (LEFEM) and nonlinear finite element (NLFEM) soil-structure interaction analyses. The NLFEM analysis is required when it becomes necessary to verify that the design meets stringent displacement control performance objectives. Both the LEFEM and NLFEM analyses can be used to verify safety with economy designs.

Table 1-3
Design and Analysis Tools for Flexible Wall Systems (Ebeling et al. 2002)

Analysis	Objective	Description	Analysis Method
RIGID 1	Final design when performance goal is safety with economy. Preliminary design when performance goal is stringent displacement control.	Beam on rigid supports analysis using apparent pressure "envelope" diagram. Apparent pressure diagram based on a total load approach. Total load is based on a factor of safety of 1.3 applied to the shear strength of the soil when the performance goal is safety with economy. Total load is based on a factor of safety of 1.5 applied to the shear strength of the soil when the performance goal is stringent displacement control.	Hand calculations
NLFEM	Final design when performance goal is stringent displacement control.	Nonlinear soil-structure finite element construction-sequencing analysis.	PC SOILSTRUCT-ALPHA

Table 1-4
Design and Analysis Tools for Stiff Wall Systems (Strom and Ebeling 2002)

Analysis	Objective	Description	Analysis Method
RIGID 1	Preliminary design tool to estimate upper anchor loads and bending moments in upper region of wall.	Beam on rigid supports analysis using apparent pressure "envelope" diagram. Apparent pressure diagram based on a total load approach. Total load is based on a factor of safety of 1.3 applied to the shear strength of the soil when the performance goal is safety with economy. Total load is based on a factor of safety of 1.5 applied to the shear strength of the soil when the performance goal is stringent displacement control.	Hand calculations
RIGID 2	Construction-sequencing analysis using classical soil pressures. Used to estimate lower anchor loads and bending moments in lower regions of wall.	Beam on rigid supports analysis. Soil-pressure distribution by classical methods, i.e., Rankine, Coulomb, etc. Active pressures used to determine anchor loads and wall bending moments based on a factor of safety of 1.0 applied to the shear strength of the soil when the performance goal is safety with economy. At-rest earth pressures used to determine anchor loads and wall bending moments based on a factor of safety of 1.5 applied to the shear strength of the soil when the performance goal is stringent displacement control. Passive pressures used to determine anchor loads and wall bending moments based on a factor of safety of 1.0 applied to the shear strength of the soil.	Hand calculations for determinate systems. CBEAMC equivalent beam analysis for indeterminate systems.
WINKLER 1	Construction-sequencing analysis to affirm results of RIGID 1 and RIGID 2 analyses.	Beam on inelastic supports analysis. Inelastic springs used to represent soil on both sides of wall. Inelastic springs used to represent anchors. R-y curves shifted to account for inelastic soil deformations.	CMULTIANC beam on inelastic supports analysis.
WINKLER 2	Construction-sequencing analysis to affirm results of RIGID 1 and RIGID 2 analyses.	Beam on inelastic supports analysis. Inelastic springs used to represent soil on excavated side of wall. Classical soil pressures applied to retained earth side of wall. Inelastic springs used to represent anchors.	CBEAMC beam on nonlinear supports analysis.
LEFEM	Construction-sequencing analysis to affirm results of RIGID 1 and RIGID 2 analyses and to evaluate 3-D effects and investigate loss of anchor effects. Used for cases where bending effects in the longitudinal direction are important.	Plate elements used to represent wall to capture redistribution effects in the longitudinal direction of the wall. Elastic springs used to represent soil on excavated side of wall. Classical soil pressures applied to retained earth side of wall. Elastic springs used to represent anchors.	Structural analysis software with plate element analysis capability.
NLFEM	Final design when performance goal is stringent displacement control.	Nonlinear soil-structure finite element construction-sequencing analysis	PC SOILSTRUCT-ALPHA.

Descriptions of the analysis methods cited in Tables 1-3 and 1-4 and used in the example problems are provided in Strom and Ebeling (2002). With respect to the WINKLER beam on inelastic spring analyses cited in these tables, there are several methods for constructing the spring load-displacement (R-y) curves. These methods are summarized in Table 1-5 and described in the first example in Strom and Ebeling (2002).

Table 1-5
Summary of R-y Curve Construction Methods (Strom and Ebeling 2001)

Method	Description
Constant of Horizontal Subgrade Reaction/ Subgrade Constant	A constant of horizontal subgrade reaction method was developed by Terzaghi (1955) for use in the evaluation of discrete wall systems. A subgrade constant method was also developed for continuous walls. Interaction distances used in the analysis are per Haliburton (1981). Methods generally provide a reasonable estimate of wall moments and shears, but often overestimate displacements.
Soletanche	FHWA-RD-81-150 presents coefficients of subgrade reaction based on information obtained from pressure meter tests. Subgrade reaction values are a function of the shear parameters of the soil. Soletanche used beam on inelastic foundation analyses, based on the Pfister coefficient of subgrade reaction values, to verify that anchor loads and computed wall displacements met performance objectives.
Reference Deflection Method	Method reported in FHWA-RD-98-066 for use in beam on inelastic foundation analyses. Displacements representing the elastoplastic intersection point of the R-y curve were established for granular and clay soils. R-y curves are shifted to account for inelastic nonrecoverable displacements. These investigators indicated that the deflection response estimated by the reference deflection method generally underpredicted displacements because it does not account for mass movements in the soil.

1.3 RIGID 1 Method

In the RIGID 1 method (Strom and Ebeling 2002), a vertical strip of the tieback wall is treated as a multispan beam supported on rigid supports located at tieback points in the upper region of the wall. The lowermost rigid support is assumed to occur at finish grade. The wall is loaded on the driving side with an apparent pressure loading. In general practice, the use of soil pressure envelopes as loadings for a beam on rigid support analysis provides an expedient method for the initial layout, and sometimes the final design of tieback wall systems. However, the soil pressure envelopes, or apparent earth pressure diagrams, were not intended to represent the real distribution of earth pressure, but instead constituted hypothetical pressures. These hypothetical pressures were a basis from which strut loads could be calculated that might be approached but would not be exceeded during the entire construction process.

The apparent pressure loading used in the example problems is in accordance with FHWA-RD-97-130. (See Figure 28 of this FHWA report for the apparent pressure diagram used for a wall supported by a single row of anchors and Figure 29 for the apparent pressure diagram used for a wall supported by multiple rows of anchors.) This information is also presented in Strom and Ebeling (2001, Figures 5.3 and 5.4).

RIGID 1 design procedures are illustrated in the example problems contained in Strom and Ebeling (2002) and in the example problems in Section 10 of FHWA-RD-97-130. When tiebacks are prestressed to levels consistent with active pressure conditions (i.e., Example 1 in Strom and Ebeling 2002), the total load used to determine the apparent earth pressure is based on that approximately corresponding to a factor of safety of 1.3 on the shear strength of the soil. When tiebacks are prestressed to minimize wall displacement (Example 2 in Strom and Ebeling 2002), the total load used to determine the apparent earth pressure is based on at-rest earth pressure coefficient conditions, or that approximately corresponding to a factor of safety of 1.5 applied to the shear strength of the soil. Empirical formulas are provided with the apparent pressure method for use in estimating anchor forces and wall bending moments.

1.4 RIGID 2 Method

As with the RIGID 1 method, a vertical strip of the tieback wall is treated as a multispan beam supported on rigid supports located at tieback points (Strom and Ebeling 2002). The lowest support location is assumed to be below the bottom of the excavation at the point of zero net pressure (Ratay 1996). Two earth pressure diagrams are used in each of the incremental excavation, anchor placement, and prestressing analyses. Active earth pressure (or at-rest earth pressure when wall displacements are critical) is applied to the driving side and extends from the top of the ground to the actual bottom of the wall. Passive earth pressure (based on a factor of safety of 1.0 applied to the shear strength of soil) is applied to the resisting side of the wall and extends from the bottom of the excavation to the actual bottom of the wall. The application of the RIGID 2 method is demonstrated in the two example problems in Strom and Ebeling (2002). The RIGID 2 method is useful for determining if the wall and anchor capacities determined by the RIGID 1 analysis are adequate for stiff tieback wall systems, and permits redesign of both flexible and stiff tieback wall systems to ensure that strength is adequate for all stages of construction. No useful information can be obtained from the RIGID 2 analysis regarding displacement demands, however.

1.5 WINKLER 1 Method

The WINKLER 1 method (described in Strom and Ebeling 2002) uses idealized elastoplastic springs to represent soil load-deformation response and anchor springs to represent ground anchor load-deformation response. The elastoplastic curves (R-y curves) representing the soil springs for the example problems are based on the reference deflection method (FHWA-RD-98-066). Other methods are available for developing elastoplastic R-y curves for beam on inelastic foundation analyses. The reference deflection method (FHWA-RD-98-066), the Haliburton (1981) method, and the Pfister method (FHWA-RD-81-150) are described in the first example problem. Elastoplastic curves can be shifted with respect to the undeflected position of the tieback wall to capture non-recoverable plastic movements that may occur in the soil during various construction stages (e.g., excavating, anchor placement, and prestressing of anchors).

This R-y curve shifting was used in both example problems to consider the non-recoverable active state yielding that occurs in the retained soil during the first-stage excavation (cantilever-stage excavation). The R-y curve shift following the first-stage excavation will help to capture the increase in earth pressure that occurs behind the wall as anchor prestress is applied, and as second-stage excavation takes place. In the two example problems in Strom and Ebeling (2002), once the upper anchor is installed, the second-stage excavation causes the upper section of the tieback wall to deflect into the retained soil—soil that has previously experienced active state yielding during first-stage excavation. The WINKLER 1 method is useful for determining if the wall and anchor capacities determined by a RIGID 1 or RIGID 2 analysis are adequate, and permits redesign of stiff tieback wall systems to ensure that strength is adequate for all stages of construction. It also provides useful information on "relative" displacement demands and facilitates redesign of the wall system when it becomes necessary to meet displacement-based performance objectives.[3]

The PC-based computer program CMULTIANC used to simulate the simplified construction sequence in the analysis of a stiff tieback wall is classified as a WINKLER 1 type analysis by Strom and Ebeling (2002). Top-down construction is assumed in this analysis procedure. This report presents three abbreviated example analyses. Strom and Ebeling (2002) compare the results from CMULTIANC and other methods of analysis for two of the example tieback walls (the Soletanche wall and Bonneville wall analyses) contained within this report.

1.6 WINKLER 2 Method

The WINKLER 2 method (Strom and Ebeling 2002) is a simple beam on inelastic foundation method that uses soil loadings on the driving side of the wall and elastoplastic soil springs on the resisting side of the wall in an incremental excavation, anchor placement, and anchor prestressing analysis. As with the WINKLER 1 method, the elastoplastic curves representing the soil springs are based on the reference deflection method, and anchor springs are used to represent the ground anchor load-deformation response. However, the WINKLER 2 method is unable to capture the effects of nonrecoverable plastic movements that may occur in the soil during various construction stages. Although not considered to be as reliable as the WINKLER 1 method, the WINKLER 2 method is useful for determining if the wall and anchor capacities determined by a RIGID 1 or RIGID 2 analysis are adequate, and the method permits redesign of stiff tieback wall systems to ensure that strength is adequate for all stages of construction. It also provides information on relative displacement demands (i.e., the effects of system alterations described in terms of changes in computed displacements) and permits redesign of the wall system to meet stringent displacement control performance objectives.

[3] At this time, the authors of this report do not propose to use WINKLER inelastic spring-based methods of analyses to predict wall displacements. However, the differences in the computed deformations of an altered wall system based on WINKLER analyses may be useful as a qualitative assessment of change in stiffness effects.

1.7 NLFEM Method

When displacements are important with respect to project performance objectives, a nonlinear finite element soil-structure interaction (SSI) analysis should be performed. In an NLFEM analysis, soil material nonlinearities are considered. Displacements are often of interest when displacement control is required to prevent damage to structures and utilities adjacent to the excavation. To keep displacements within acceptable limits, it may be necessary to increase the level of prestressing beyond that required for basic strength performance. An increase in tieback prestressing is often accompanied by a reduction in tieback spacing. As tieback prestressing is increased, wall lateral movements and ground surface settlements decrease. Associated with an increased level of prestress is an increase in soil pressures. The higher soil pressures increase demands on the structural components of the tieback wall system. General-purpose NLFEM programs for two-dimensional plane strain analyses of SSI problems are available (e.g., PC-SOILSTRUCT-ALPHA) to assess displacement demands on tieback wall systems. These programs can calculate displacements and stresses due to incremental construction and/or load application and are capable of modeling nonlinear stress-strain material behavior. An accurate representation of the nonlinear stress/strain behavior of the soil, as well as proper simulation of the actual (incremental) construction process (excavation, anchor installation, anchor prestress, etc.), in the finite element model is essential if this type of analysis is to provide meaningful results. This type of analysis is referred to as a <u>complete</u> construction sequence analysis (versus the <u>simplified</u> construction sequence analysis of CMULTIANC). See Strom and Ebeling (2001) for additional details regarding nonlinear SSI computer programs for displacement prediction.

1.8 Factors Affecting Analysis Methods and Results

1.8.1 Overexcavation

Overexcavation below ground anchor support locations is required to provide space for equipment used to install the ground anchors. It is imperative that the specified construction sequence and excavation methods are adhered to and that overexcavation below the elevation of each anchor is limited to a maximum of 2 ft. Construction inspection requirements in FHWA-SA-99-015 require inspectors to ensure that overexcavation below the elevation of each anchor is limited to 2 ft, or as defined in the specifications. In the Bonneville temporary tieback wall example, an overexcavation of 5.5 ft was considered for the initial design. This should be a "red flag" to the designer that a construction-sequencing evaluation is needed, and that such an evaluation will likely demonstrate that the maximum force demands on the wall and tiebacks will occur during intermediate stages of construction rather than for the final permanent loading condition. For additional information on the effect of overexcavation on tieback wall performance, see Yoo (2001).

1.8.2 Ground anchor preloading

Unless anchored walls are prestressed to specific active stress levels and their movement is consistent with the requirements of the active condition at each construction stage, the lateral earth pressure distribution will be essentially nonlinear with depth, and largely determined by the interaction of local factors. These may include soil type, degree of fixity or restraint at the top and bottom, wall stiffness, special loads, and construction procedures (Xanthakos 1991). To ensure that ground anchor prestressing is consistent with active state conditions, the designer will generally limit anchor prestress to values that are between 70 and 80 percent of those determined using an equivalent beam on rigid supports analysis based on apparent pressure loadings (FHWA-RD-81-150). However, this may produce wall movements toward the excavation that are larger than tolerable, especially in cases where structures critical to settlement are founded adjacent to the excavation. Larger anchor prestressed loads are generally used when structures critical to settlement are founded adjacent to the excavation. Selection of an arbitrary prestress load can be avoided by using the WINKLER 1 method beam on inelastic foundation analysis described previously. This type of analysis permits the designer to relate wall movement to anchor prestress and/or anchor spacing in order to produce tieback wall performance that is consistent with displacement performance objectives.

1.9 Construction Long-Term, Construction Short-Term, and Postconstruction Conditions

For a free-draining granular backfill, the pore-water pressure does not usually include excess pore-water pressures generated in the soil by changes in the total stress regime due to construction activities (excavation, etc.). This is because the rate of construction is much slower than the ability of a pervious and free-draining granular soil to rapidly dissipate construction-induced excess pore-water pressures.

However, for sites containing soils of low permeability (soils that drain slower than the rate of excavation/construction), the total pore-water pressures will not have the time to reach a steady-state condition during the construction period. In these types of slow-draining, less permeable soils (often referred to as cohesive soils), the shear strength of the soil during wall construction is often characterized in terms of its undrained shear strength. The horizontal earth pressures are often computed using values of the undrained shear strength for these types of soils, especially during the short-term, construction loading condition (sometimes designated as the undrained loading condition—where the term undrained pertains to the state within the soil during this stage of loading).

As time progresses, however, walls retained in these types of soils can undergo two other stages of construction loading: the construction long-term (drained or partially drained) condition and the postconstruction/permanent (drained) condition. Under certain circumstances, earth pressures may be computed in poorly drained soils using the Mohr-Coulomb (effective stress-based) shear strength parameter values for the latter load case(s).

Liao and Neff (1990), along with others, point out that all three stages of loading must be considered when designing tieback wall systems, regardless of soil type. As stated previously, for granular soils, the construction short- and long-term conditions are usually synonymous since drainage in these soils occurs rapidly. Differences in the construction short- and long-term conditions are generally significant only for cohesive soils. Changes in the groundwater level (if present) before and after anchor wall construction, as well as postconstruction/permanent, must be considered in these evaluations. Designers must work closely with geotechnical engineers to develop a soils testing program that will produce soil strength parameters representative of each condition—construction short term, construction long term, and postconstruction. The program should address both laboratory and field testing requirements. Additional information on construction short-term, construction long-term, and postconstruction condition earth-pressure loadings can be found in Strom and Ebeling (2001). Methods used to estimate long-term (drained) shear strength parameters for stiff clay sites are presented in Appendix A of Strom and Ebeling (2002).

1.10 Construction-Sequencing Analyses

Tieback wall design procedures vary in practice, depending on whether the tieback wall is considered to be flexible or stiff. Flexible wall systems include the following:

- Vertical sheet-pile systems.
- Soldier beam and lagging systems.

As stated previously, flexible wall systems are often designed using an equivalent beam on rigid support method of analysis with an apparent earth pressure envelope loading. The flexible wall system design approach is illustrated herein with respect to the two stiff tieback wall examples in Strom and Ebeling (2002) in order to be able to compare the results with those obtained using the simplified construction-sequencing type analyses (of CMULTIANC). The flexible wall design process is also illustrated in Ebeling et al. (2002).

Stiff tieback wall systems include the following:

- Secant cylinder pile systems.
- Continuous reinforced concrete (tremie wall) systems.
- Soldier beam–tremie wall systems.

In practice, the stiff tieback wall systems employ some type of construction-sequencing analysis, i.e., staging analysis, in which the anchor loads, wall bending moments, and possibly wall deflections are determined for each construction stage. In general, designers recommend against application of the apparent pressure diagram approach, used for flexible tieback wall systems, for the design of stiff tieback wall systems (Kerr and Tamaro 1990). Equivalent beam on rigid support methods and beam on inelastic foundation methods are those methods most commonly used in the construction-sequencing analysis. Classical earth pressure theories (Rankine, Coulomb, etc.) are generally used in the equivalent beam on rigid support method. Profiles of lateral earth pressures on both sides of the wall are developed by classical theory with active pressures acting on the driving side and passive pressures acting on the resisting side. An at-rest pressure profile may be used to represent driving side earth pressures for stiff wall systems that are required to meet stringent displacement performance objectives. The beam on inelastic foundation method allows displacement performance to be assessed directly (in a relative but ***not*** an absolute sense). It is therefore preferred over the equivalent beam on rigid support method for tieback wall systems where displacement performance is critical. Both the equivalent beam on rigid support method and the beam on inelastic foundation method are demonstrated in a simplified construction-sequencing analysis with respect to the design and evaluation of two stiff tieback wall systems in Strom and Ebeling (2002). Two of these example CMULTIANC analyses are presented in this report.

2 Computer Program CMULTIANC

2.1 Introduction

This report describes the computer program CMULTIANC, which performs analyses simulating the construction sequence of a stiff, multiply anchored tie-back wall. "Stiff" walls are described by Strom and Ebeling (2001, 2002). The analyses are performed using a one-dimensional finite element method described by Dawkins (1994a, 1994b).

2.2 Disclaimer

The program is based on criteria provided by the Information Technology Laboratory, Vicksburg, MS, U.S. Army Engineer Research and Development Center. The program has been checked within reasonable limits to assure that the results are accurate within the limitations of the procedures employed. However, there may exist combinations of parameters which may cause the program to produce questionable results. It is the responsibility of the user to judge the validity of the results reported by the program. The author assumes no responsibility for the design or performance of any system based on the results of this program.

2.3 System Overview

The procedures employed in this program are applicable to stiff anchored tieback walls as described in Strom and Ebeling (2001, 2002).

The general wall/soil system shown in Figure 2-1 may be used for either cantilever or anchored walls. The system is assumed to be uniform perpendicular to the plane of the figure. A typical 1-ft slice of the uniform system is used for analysis.

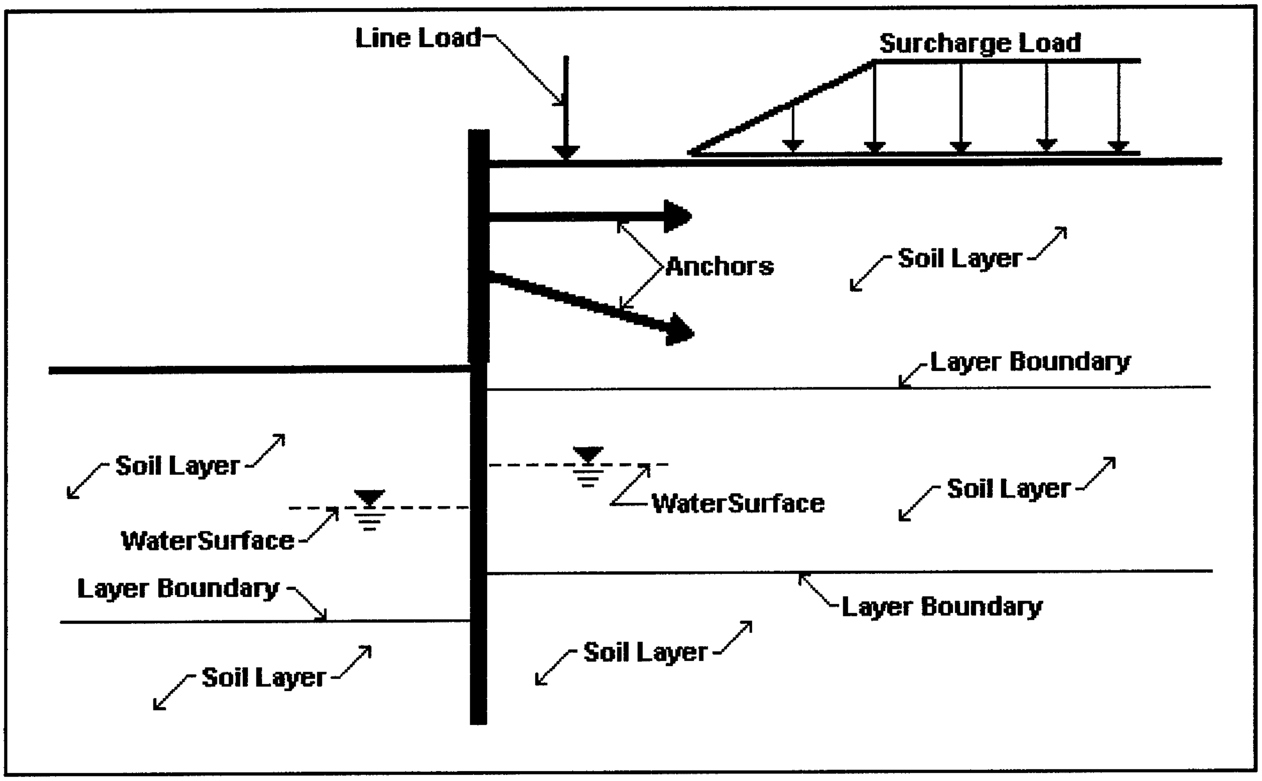


Figure 2-1. Schematic of wall/soil system

The typical 1-ft slice of the wall is assumed to be composed of 1 to 10 prismatic segments sharing a common initially straight and vertical centroidal axis. The elevations at which changes in wall cross-section properties occur, as well as the cross-section properties (moment of inertia, cross-section area, and modulus of elasticity), must be supplied as input to the program. The material of the wall is assumed to be linearly elastic.

2.4 Anchors

Up to five anchors may be attached to the wall at elevations between the top and bottom of the wall. It is implicitly assumed that all anchors extend away from the wall to the right (as shown in Figure 2-1). For inclined anchors, the program uses the horizontal components of the anchor lock-off load and anchor stiffness in the analysis.

2.5 Excavation Elevations

Up to five excavation elevations may be specified. Anchor installation and excavation proceed in sequence from the top down. The last excavation elevation is assumed to specify the final surface after the last anchor is installed.

2.6 Soil Profile

A different soil profile, composed of 1 to 11 distinct layers, is assumed to exist on either side of the wall. Boundaries between subsurface layers are assumed to be straight horizontal lines. Soil layers are assumed to extend ad infinitum away from the wall. The lowest layer described on either side of the wall is assumed to extend ad infinitum downward.

2.6.1 Unit weights

Each layer is characterized by two unit weights: moist and saturated.

a. *Saturated unit weight γ_{sat} (pcf):* Used for submerged drained soil to determine the buoyant unit weight according to:

$$\gamma' = \gamma_{sat} - \gamma_w \tag{2-1}$$

where

γ' = buoyant unit weight

γ_w = unit weight of water

b. *Moist unit weight γ_{mst} (pcf):* The moist unit weight is used for all soil above the water surface.

2.6.2 Strength properties

Three strength properties are required for each cohesionless (drained) layer: angle of internal friction and active and passive angles of wall friction. A single strength property, undrained strength, is required for each undrained cohesive layer.

c. *Undrained shear strength s_u (psf).*

d. *Effective angle of internal friction for drained soil ϕ' (deg).* ϕ' must be less than or equal to 45 deg.

e. *Angle of wall friction for drained soil $\delta_{a/p}$ (deg).* $\delta_{a/p}$ must be positive and must be less than ϕ'. $\delta_{a/p}$ decreases active soil pressures and increases passive soil pressures. Different angles of wall friction may be specified for active and passive soil pressure calculation.

2.7 Water

When water is present in the soil profile, water levels for the initial soil profiles may be at any elevation at or below the top of the wall. The water level on the right side of the wall as shown in Figure 2-1 is assumed to be static and is unchanged during the construction sequence. Water elevations on the left side must also be specified for each excavation described for the construction sequence. The water elevation for an excavation must be at or below the initial water elevation on the left side and at or below the elevation specified for the previous excavation.

2.8 Vertical Surcharge Loads

Vertical surcharge loads may be applied as line loads or distributed loads to the right-side surface:

a. *Line loads.* Vertical line loads may be applied to the right-side surface.

b. *Distributed loads.* Five distributed load variations are available:

(1) *Uniform load.* A uniform surcharge is constant and extends ad infinitum over the entire soil surface. Only one uniform load may be prescribed on the right-side surface.

(2) *Strip loads.* Strip loads are uniformly distributed over a finite segment of the soil surface. Several strip loads may be applied to the right-side surface.

(3) *Ramp load.* A ramp load begins at zero at some distance from the wall, increases linearly to a maximum value, and continues ad infinitum as a uniform load. Only one ramp load may be applied to the right-side surface.

(4) *Triangular loads.* A triangular load begins at zero at some distance from the wall, increases linearly to a maximum, then decreases to linearly to zero. Several triangular loads may be applied to the right-side surface.

(5) *Variable distributed load.* A variable distributed loading is described by a sequence of distance/load points. The load is assumed to vary linearly between adjacent points.

2.9 Limiting Soil and Water Pressures

Horizontal loads are imposed on the structure by the surrounding soil (including the effects of surface surcharges), the effects of anchors, and water. Water pressures are unaffected by displacements. Soil pressures depend on both the magnitude and direction of wall displacements and vary between limiting active and passive pressures.

2.10 Calculation Points

Force magnitudes and wall response are calculated at the following points:

a. At 1-ft intervals beginning at the top of the wall.

b. At the top and bottom of the wall and at the locations of changes in cross section.

c. At the intersection of the soil surface and soil layer boundaries on each side of the wall.

d. At the intersection of the water surface on each side of the wall.

e. At the location of the anchors.

f. At other locations to establish the resultant force or pressure distribution as necessary for the analysis.

2.11 Active and Passive Pressures

2.11.1 Undrained (cohesive) soils

Active and passive soil pressures, p_{Ah} and p_{Ph}, respectively, in a homogeneous undrained (cohesive) soil profile are calculated from:

$$p_{Ah} = p_v - 2s_u \tag{2-2}$$

$$p_{Ph} = p_v + 2s_u \tag{2-3}$$

where p_v is the cumulative vertical pressure using γ_{mst} for soil above water and γ_{sat} for submerged soil plus any uniform surcharge.

2.11.2 Drained (cohesionless) soils

Active and passive soil pressures for a homogeneous drained (cohesionless) soil profile are calculated using earth pressure coefficients as described in the next section.

2.11.3 Pressure coefficients

The earth pressure coefficients are given by:

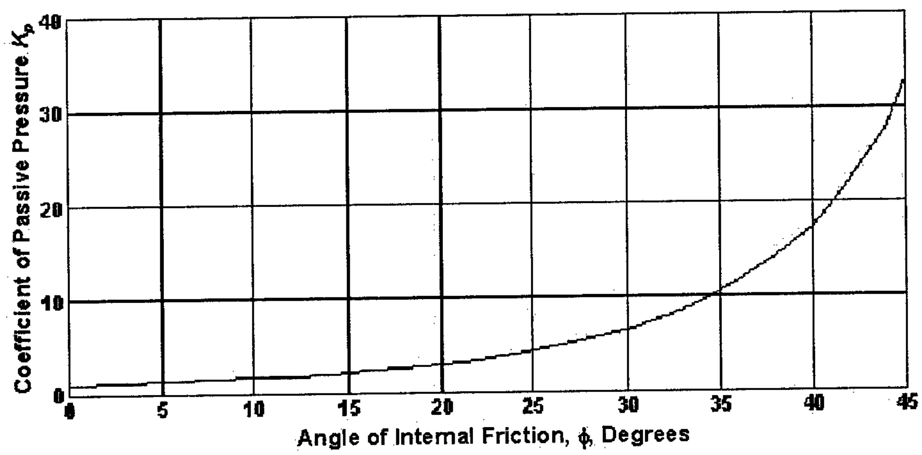
a. Active coefficient:

$$K_A = \left[\frac{\cos\phi}{1 + \sqrt{\dfrac{\sin(\phi + \delta_a)\sin\phi}{\cos\delta_a}}} \right]^2 \cdot \frac{1}{\cos\delta_a} \tag{2-4}$$

b. *Passive coefficient for* $\delta_p \le \phi/2$ *:*

$$K_p = \left[\frac{\cos\phi}{1-\sqrt{\dfrac{\sin(\phi+\delta_p)\sin\phi}{\cos\delta_p}}}\right]^2 \cdot \frac{1}{\cos\delta_p} \qquad (2\text{-}5)$$

c. *Passive coefficient for* $\delta_p > \phi/2$ *:* K_p is obtained from the curve and reduction factors for a log-spiral solution as shown in Figure 2-2.



a. Passive pressure coefficient by log-spiral method ($\delta = \phi$)

ϕ \ δ/ϕ	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
10	0.978	0.962	0.946	0.929	0.912	0.898	0.881	0.864
15	0.961	0.934	0.907	0.881	0.854	0.830	0.803	0.775
20	0.939	0.901	0.862	0.824	0.787	0.752	0.716	0.678
25	0.912	0.860	0.808	0.759	0.711	0.666	0.620	0.574
30	0.878	0.811	0.746	0.686	0.627	0.574	0.520	0.467
35	0.836	0.752	0.674	0.603	0.536	0.475	0.417	0.362
40	0.783	0.682	0.592	0.512	0.439	0.375	0.316	0.262
45	0.718	0.600	0.500	0.414	0.339	0.276	0.221	0.174

b. Reduction factor of K_p (for $\delta = \phi$) for various ratios of δ/ϕ

Figure 2-2. Log-spiral passive pressure coefficients (after Department of the Navy 1982)

The vertical pressure p_v at each point is calculated using the effective unit weight for the soil above that point plus any uniform surcharge.

Horizontal earth pressures are calculated as follows:

a. Active pressures.

$$p_{Ah} = K_A \cdot p_v \cdot \cos \delta_P \tag{2-6}$$

b. Passive pressures.

$$p_{Ph} = K_P \cdot p_v \cdot \cos \delta_p \tag{2-7}$$

2.11.4 Profiles with interspersed undrained and drained layers

When a change in either ϕ, s_u, or unit weight occurs at a boundary between layers, dual pressure values are calculated using the soil properties above and below the boundary. The vertical pressure increases with total unit soil weight in undrained (cohesive) layers and with effective unit weight in drained (cohesionless) layers.

2.11.5 Pressures due to surcharge loads

The contribution of surcharges (other than a uniform surcharge) to horizontal pressures is calculated from the theory of elasticity according to Figure 2-3.

2.12 Water Pressures

Hydrostatic pressures are applied to the wall when the water level on either side is above the bottom of the wall and the soil is drained. Water pressures in undrained soils are incorporated in the soil pressures, and additional water pressures in undrained layers are set to zero. Potential water pressure distributions are illustrated in Figure 2-4.

2.13 Nonlinear Soil and Anchor Springs

The soil pressure or anchor force exerted on the wall at any point is assumed to depend only on the displacement at that point (i.e., the Winkler assumption). In effect, the Winkler assumption results in treating the soil and anchors as isolated translation resisting elements.

Under the Winkler assumption, the soil system may be visualized as a system of independent columns with curves representing the soil pressure-displacement relationship for the soil columns as shown in Figure 2-5.

Soil-structure interaction at each node is represented by two concentrated springs with characteristics obtained from soil pressures immediately above and below the node as illustrated in Figure 2-6 for the soil on the right side.

Limiting forces are calculated as follows:

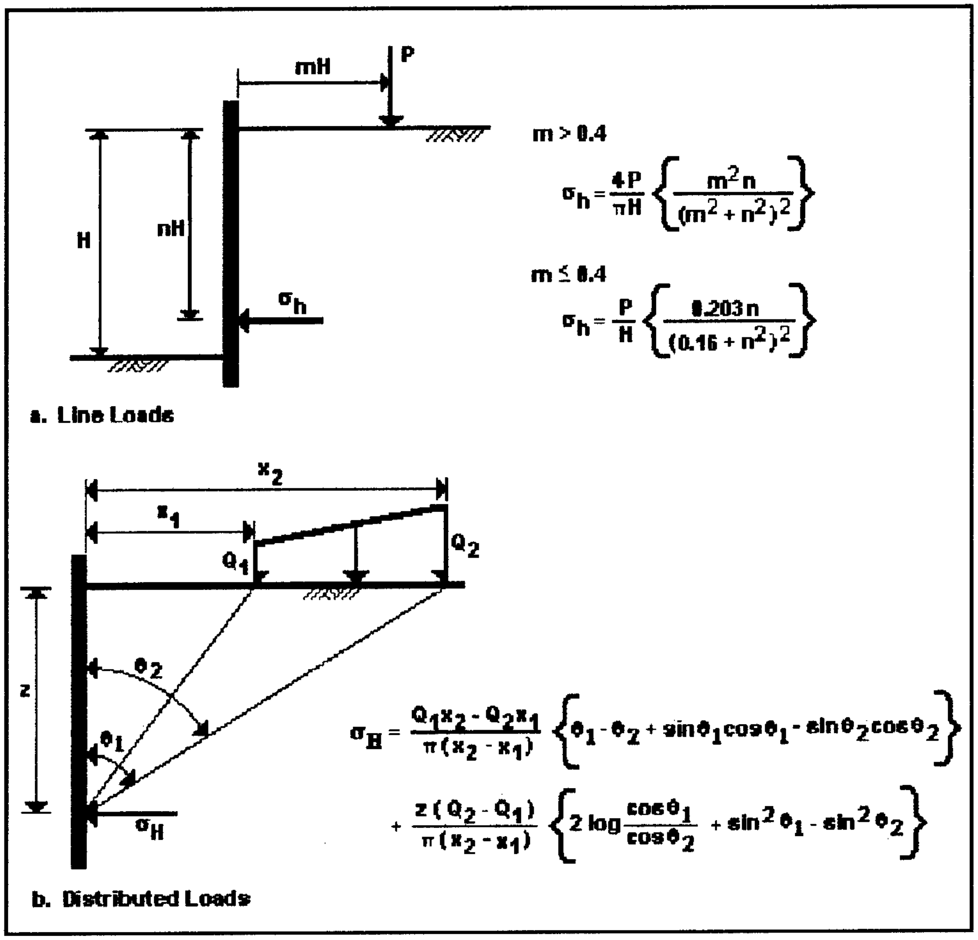


Figure 2-3. Pressure calculations for surcharge loads

a. *For the curve below node i:*

$$F_{ai} = \frac{h}{6}\left(2 \cdot p_{ai} + p_{aj}\right) \tag{2-8}$$

$$F_{pi} = \frac{h}{6}\left(2 \cdot p_{pi} + p_{pj}\right) \tag{2-9}$$

b. *For the curve above node j:*

$$F_{aj} = \frac{h}{6}\left(p_{ai} + 2 \cdot p_{aj}\right) \tag{2-10}$$

$$F_{pj} = \frac{h}{6}\left(p_{pi} + 2 \cdot p_{pj}\right) \tag{2-11}$$

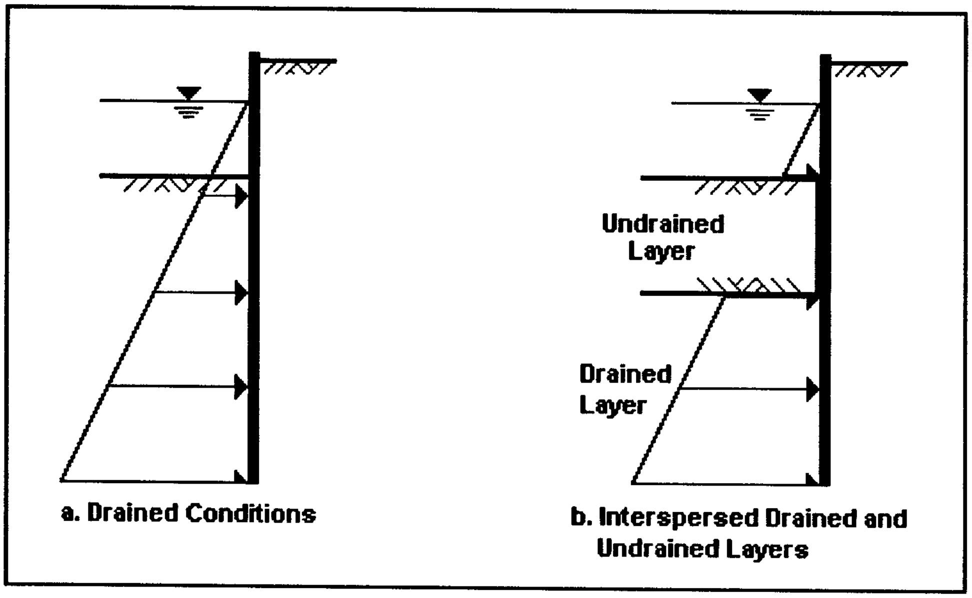


Figure 2-4. Water pressures

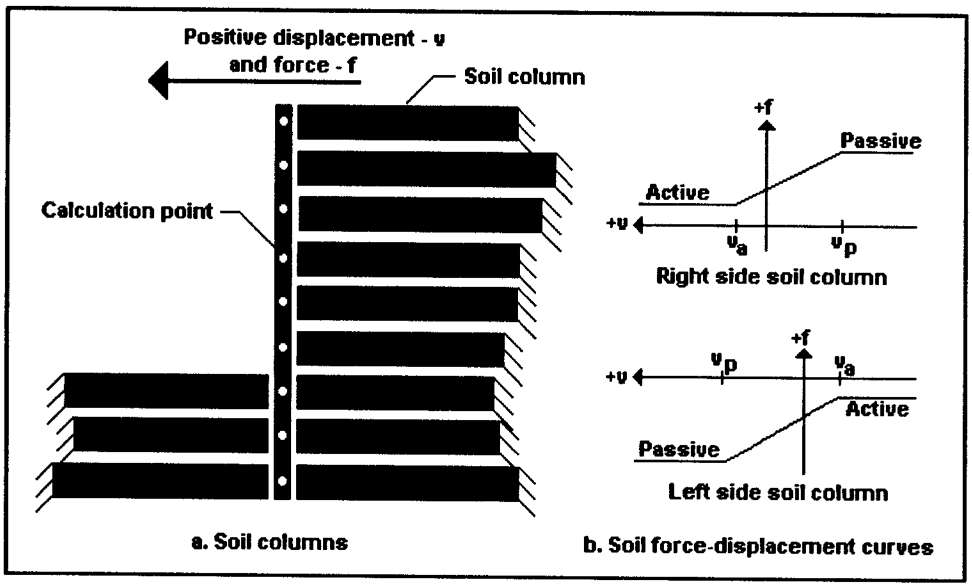


Figure 2-5. Nonlinear soil springs

Although the actual force-displacement relationship is nonlinear, it is assumed that the force varies linearly between active and passive conditions.

2.14 Displacements at Limiting Forces

The displacements v_a and v_p at which a soil spring attains the limit force are dependent on the soil type: "sand" or "clay." Unless "reference deflections" (FHWA-RD-98-066) are specified by the user, default displacements at the limit forces in Table 2-1 are used.

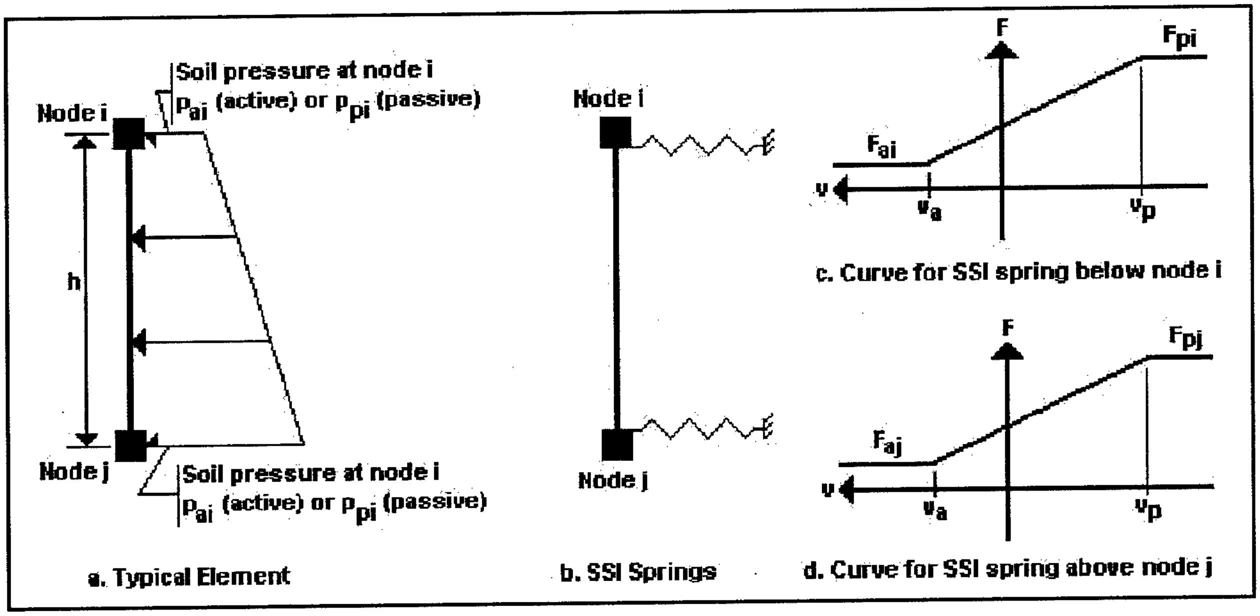


Figure 2-6. Concentrated soil springs

Table 2-1
Reference Displacements

Soil Type	Limit Displacement, in. Active	Passive
Sand	0.05	0.5
Clay: s_u < 2 tsf	0.2	1.0
Clay: 2 tsf < s_u < 4 tsf	0.16	0.8
Clay: s_u > 4 tsf	0.12	0.4

2.15 Shifted Soil Spring Curves

In the initial solution, soil springs are assigned displacement values at limiting pressures as described previously. Due to the initial loading, wall deflections exceed the reference displacement corresponding to the active force. During subsequent loading, displacements tend toward the passive condition. To account for the increased soil stiffness on reloading, the soil spring curves are shifted (FHWA-RD-98-066) as shown in Figure 2-7.

2.16 Anchor Springs

All anchors are assumed to be attached to the right side of the wall and to extend away from the wall to the right. The characteristics of anchors accommodated by the program are shown in Figure 2-8.

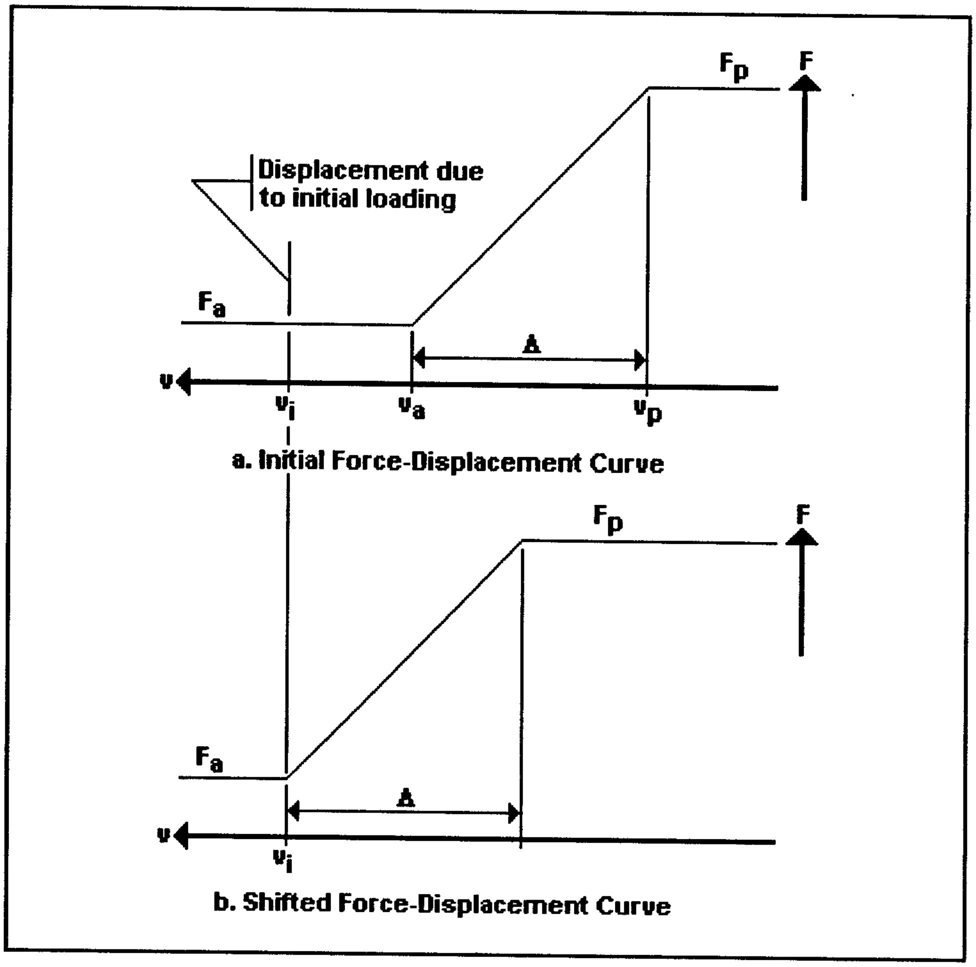


Figure 2-7. Shifted SSI soil springs

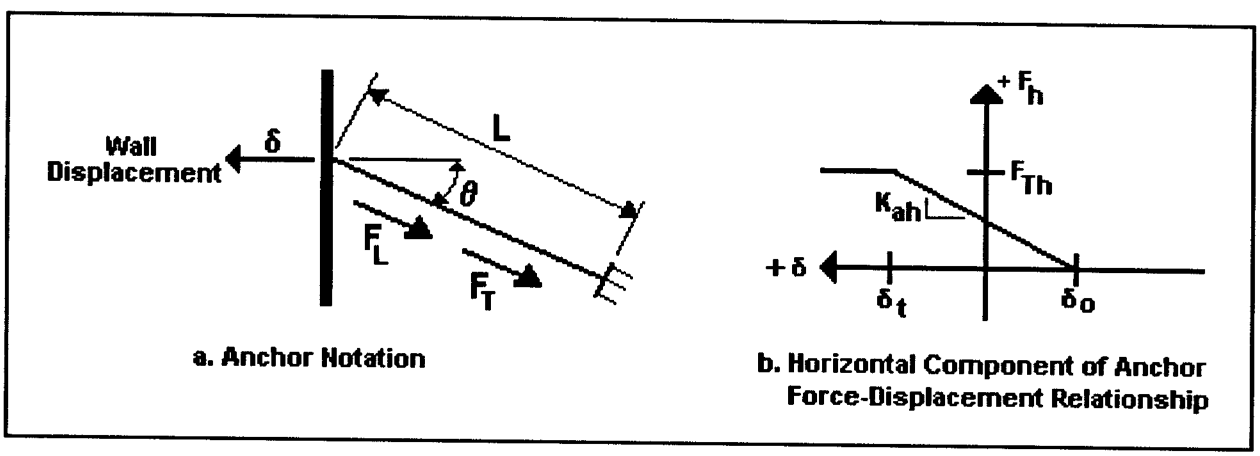


Figure 2-8. Nonlinear anchor spring

A flexible anchor acts as a nonlinear concentrated spring in which the anchor force varies with anchor deformation along its line of action as shown in Figure 2-8. The anchor lock-off load F_L and the ultimate anchor tensile strength F_T are forces along the line of action of the inclined anchor. The anchor is characterized by the properties modulus of elasticity E, cross-section area A, effective length L, slope θ, and plan spacing between adjacent anchors s.

CMULTIANC deals only with horizontal displacement of the wall. Consequently, the force-displacement relationship for the anchor spring must be expressed by the horizontal components of anchor force and spring stiffness. During the construction sequence simulation, a force equal to the horizontal component of the anchor lock-off load ($F_L \cos\theta$) is applied at the point of anchor attachment. After the displacements due to the lock-off load are determined, the lock-off load is replaced by a nonlinear concentrated anchor spring. The force-deformation relationships for the anchor spring are obtained from the following expressions.

The horizontal component of the anchor spring stiffness per foot of wall is given by

$$K_{ah} = \left(\frac{EA}{Ls}\right) \cos^2\theta \tag{2-12}$$

Defining displacements for the anchor spring force-displacement relationship are given by

$$\delta_o = \delta_L - F_{Lh} / K_{ah} \tag{2-13}$$

$$\delta_t = \delta_o + F_{Th} / K_{ah} \tag{2-14}$$

where

$$F_{Lh} = \frac{F_L}{s} \cos\theta$$

is the horizontal component of the anchor lock-off load per foot of wall,

$$F_{Th} = \frac{F_T}{s} \cos\theta$$

is the horizontal component of the anchor ultimate strength

δ_L = lateral displacement of the point of attachment from the solution with the anchor lock-off load F_{Lh} applied.

For deformation beyond δ_t, the anchor force is constant at F_{Th}. For deformations intermediate to δ_t and δ_o, the anchor force-deformation relationship may be represented as a combination of a concentrated force and a linear concentrated spring. The anchor force and displacement reported by the program are components along the line of action of the anchor. The reported anchor force is the TOTAL (NOT per foot of wall) force in the anchor.

2.17 Finite Element Model

The one-dimensional finite element model of the wall/soil system is shown in Figure 2-9. Nodes are located at the points used for calculating soil pressures.

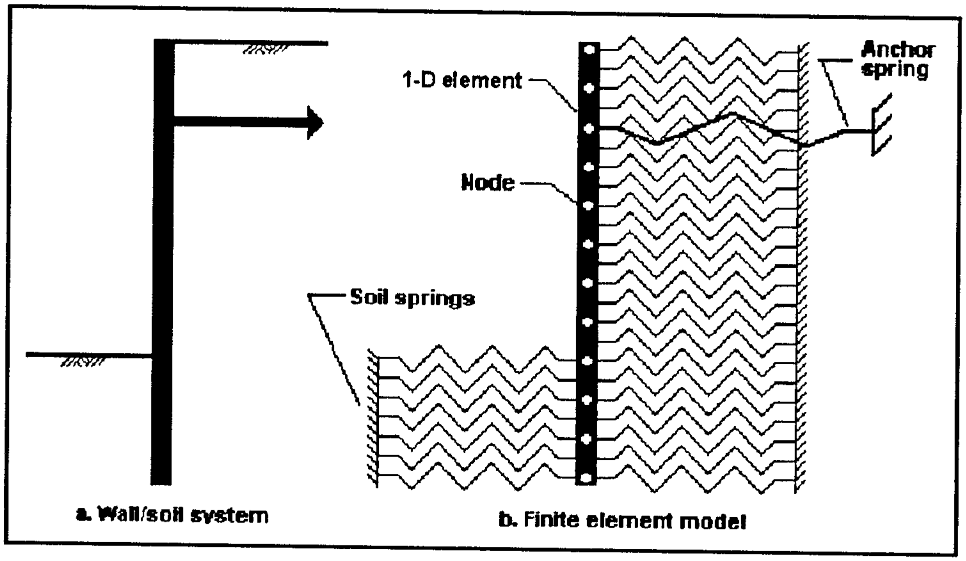


Figure 2-9. Finite element model

2.17.1 Typical element

Figure 2-10 shows a typical prismatic, linearly elastic element between adjacent nodes.

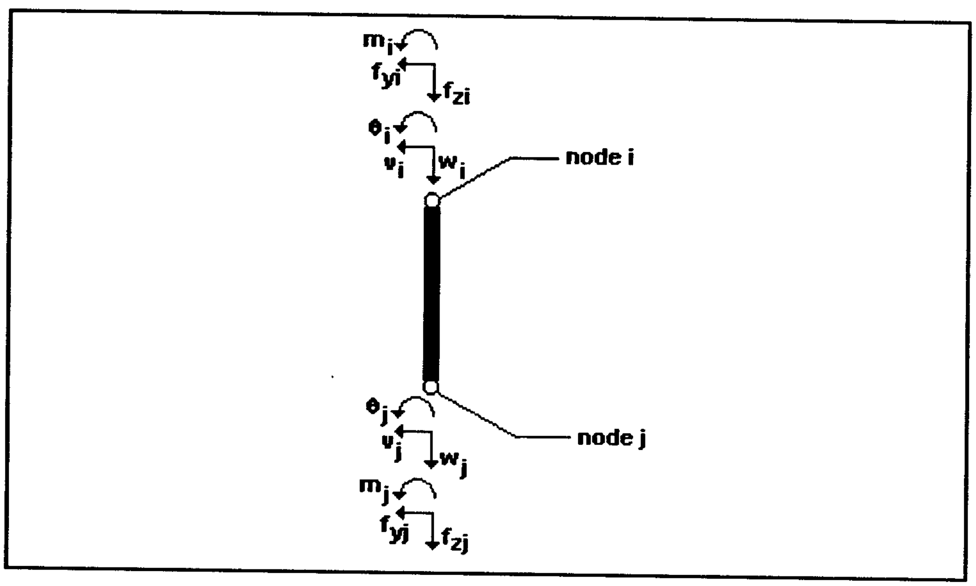


Figure 2-10. Typical element

2.17.2 Typical node

A free body of a typical node in the model is shown in Figure 2-11.

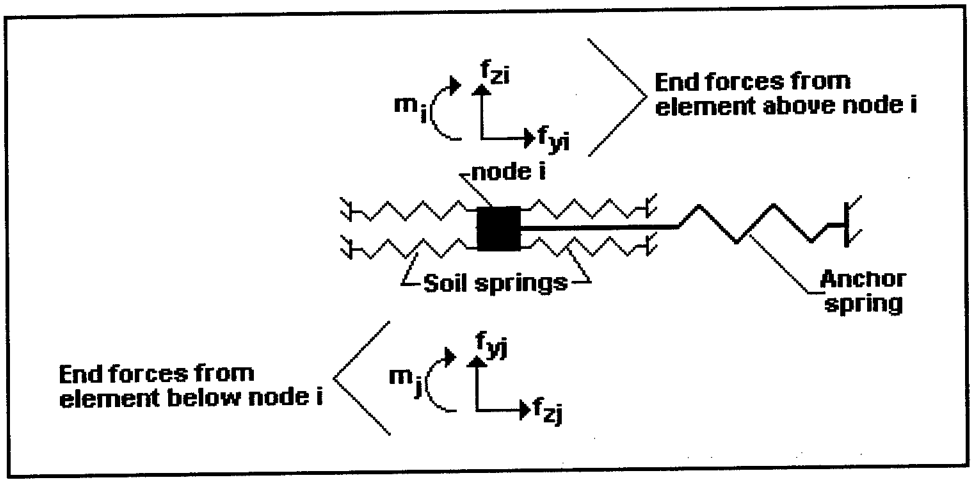


Figure 2-11. Typical node

2.18 External Supports

Restraint of lateral displacements is provided primarily by the elastic components of the soil and anchor springs. For some types of construction the bottom of the wall is keyed into rock, which effectively prevents one or more of the displacement components of the base. To represent this condition, the user may specify a free end (both lateral and rotational displacements free to occur); a fixed condition (both lateral and rotational displacements equal to zero); or a pinned condition (zero lateral displacement with rotational displacement free to occur).

2.19 Method of Solution

The procedures for analyzing one-dimensional finite element models of the type employed for the wall/soil system are presented by Dawkins (1994b) (CBEAMC). In summary, a matrix relationship is established among the end forces, end displacement, loads, and soil springs on each element. Combination of the element force-displacement relationships with nodal loads and anchor effects at each node results in a system of 3N (N nodes in the model) simultaneous equations, which are solved for the nodal displacements. Because the nodal displacements must be known before soil and anchor spring characteristics can be evaluated, iterative solutions are performed until compatibility of forces and displacements is achieved.

2.20 Stability of Solution

If the nodal displacements are excessive, the elastic component of the soil and/or anchor springs may not be present. If all elastic restraint against lateral displacement is lost, the wall/soil system is unstable. The program checks for "reasonable" displacements during each iteration and terminates execution if instability is indicated.

2.21 Computer Program

The computer program CMULTIANC is menu driven to provide flexibility of control. Input data may be provided from a predefined data file or from the user's keyboard during execution. Input data may be edited from the keyboard at any time. The program generates input and output files as well as providing for graphical display of input data and results of the solution.

The menu on the main screen consists of the following main and submenu items:

a. **File Menu:** The **File Menu** comprises the following submenu items:

(1) **New:** Allows saving any unsaved input or output data; initializes and/or erases all data variables.

(2) **Open:** Allows saving any unsaved input or output data; initializes and/or erases all data variables; displays the Open File dialog box to permit a predefined input data file to be read.

(3) **Save:** Allows saving any input and/or output data files at any time.

(4) **Print:** Allows the input and/or output files to be printed at any time.

(5) **Exit:** Allows saving any unsaved input or output data; terminates execution and unloads CMULTIANC.

b. **Edit Menu:** Allows saving any unsaved input or output data; permits editing and/or entering input data from the user's keyboard.

c. **View Menu:** The **View Menu** comprises the following submenu items:

(1) **Current Input File:** Displays the current input data in Input Data File format.

(2) **Output File:** Displays the current output file.

(3) **Input Plots:** Displays schematics of system geometry, surface surcharges, and horizontal loads.

(4) **Limiting Soil and Water Pressures:** Displays graphs of active and passive soil pressures and net water pressure.

(5) **Results Plots:** Displays graphs of deflections, moment diagram, shear diagram, and final soil pressures.

d. **Solve Menu:** Initiates solution of the problem and allows stepping through the construction sequence with the following submenu items:

(1) **Generate Limiting Soil Pressures and SSI curves.**

(2) **Solve for Initial Displacements.**

(3) **Shift SSI Curves.**

(4) **Solve with Shifted SSI Curves.**

(5) **Install Anchors in Sequence.**

(6) **Evaluate Effects of Excavation in Sequence.**

e. **Help Menu:** Invokes the CMULTIANC Help File.

2.22 Input Data Files

Input data may be supplied from a predefined permanent file or from the user's keyboard during execution. Input data are described in Appendix A, and an abbreviated input guide is given in Appendix B. Whenever data are entered from the keyboard, either initially or by editing existing data, the program generates a temporary file in input file format for storing the data. The temporary file may be saved as a permanent file at any time. Unless the temporary file is saved, existing input is lost when the program is exited or when existing data are edited during execution.

2.23 Output Data File

As soon as input data are read from a permanent file or entered from the keyboard, a temporary output file is generated. The temporary output file may be saved as a permanent file at any time during execution. Unless the temporary output file is saved as a permanent file, output data will be lost when the program is exited or when new input data are provided. The temporary (permanent) output file contains the following information:

a. *Echoprint of input data:* Presents a listing of input data with headings and appropriate units. The echoprint is automatically generated on completion of input.

b. *Limiting soil and water pressures:* As soon as active and passive soil pressures on each side of the wall and water pressures have been calculated, a tabular listing of these data is added to the temporary output file.

c. *SSI curve data:* At each stage of the construction sequence, current SSI curve data are added to the output file.

d. Results of solution: As soon as the solution for each stage of the construction sequence has been successfully completed, a complete tabulation of results is appended to the output file. This tabulation contains a summary of maximum axial and lateral displacements, bending moment, shear, and soil pressures and a listing of lateral and axial displacements, axial force, shear force, bending moment, and left-side and right-side soil pressure at each calculation point.

2.24 Graphics

The following graphic displays of input data are provided by the program:

a. **System:** A schematic showing the wall, any anchors, the soil surface, soil layer boundaries, and water levels on each side of the wall.

b. **Surcharge Loads:** Schematics of vertical line, uniform, strip, ramp, triangular, and/or variable loads applied to the soil surface.

c. **Limiting Soil and Water Pressures:** Plots of active, at-rest, and passive soil pressures for each side of the wall and net water pressures when water elevation data are provided.

d. **Results:** Following a successful solution, plots are available for lateral displacements, shear forces, bending moments, and final soil pressures throughout the length of the wall.

2.25 Construction Sequence Simulation

2.25.1 Input data

It is assumed that the input data, whether entered from the keyboard or from a data file, contain data for all system components including anchors to be installed and excavation elevations to be encountered during the construction sequence.

The soil profile for the right side is unchanged during the construction sequence. The initial soil surface for the left side is assumed to be below the elevation of the topmost anchor. The left-side profile will be revised as the construction sequence proceeds.

All pertinent data resulting from each stage in the sequence are appended to the output file, which may be examined at any time.

2.25.2 Stage 1: Initial conditions

The first stage of the solution entails evaluation of limiting soil pressures and establishment of the soil force-displacement spring (SSI) curves for zero wall displacements for the right- and left-side soil profiles described previously. All anchors are inactive during this stage.

2.25.3 Stage 2: Solution for initial conditions

A solution is performed for the displacements and system forces for the initial conditions.

2.25.4 Stage 3: Shift of SSI curves

The wall displacements from Stage 2 are compared with the deformation corresponding to the initiation of the active plateau for each SSI curve on the left side. The SSI curve is shifted whenever the active plateau is attained.

2.25.5 Stage 4: Solution with shifted SSI curves

The solution with the shifted SSI curves should duplicate the solution from Stage 2. This solution is an indication that the SSI curves have been correctly shifted.

2.25.6 Stage 5: Top anchor installation

2.25.6.1 Stage 5a: Application of anchor lock-off load. A horizontal force equal to the horizontal component of the anchor lock-off load per foot of wall is applied in four increments at the elevation of the anchor, and a solution for this condition is performed.

2.25.6.2 Stage 5b: Application of anchor spring. The deflection at the anchor together with anchor tension capacity and anchor stiffness are used to develop the characteristics of the nonlinear anchor spring. The spring is evaluated so that the force in the spring at the anchor elevation is equal to the anchor lock-off load. The force representing the anchor lock-off load is removed, and a solution with the anchor spring in place is performed. The results of this solution should duplicate those from Stage 5a.

2.25.7 Stage 6: Excavation

The soil on the left side down to the first (last if only one anchor is specified) excavation elevation is removed. If water data are provided, the water level on the left side is altered to the elevation specified for the current excavation. The limiting soil (and water) pressures and SSI curves are reevaluated for the new left side profile, and a solution is performed.

2.25.8 Subsequent stages

Stages 5 and 6 are repeated until all anchors have been installed and the final excavation is performed.

2.26 Units and Sign Conventions

Units and sign conventions assumed for input and output data are shown in Table 2-2.

Table 2-2
Units and Sign Conventions

Item	Unit	Sign Convention
Horizontal distances	ft	Always positive
Elevations	ft	Positive or negative, decreasing downward
Modulus of elasticity	psi	Always positive
Wall moment of inertia	in.^{4}	Always positive
Wall cross-section area	in.^{4}	Always positive
Soil unit weight	pcf	Always positive
Angle of internal friction	deg	Always positive
Cohesion	psf	Always positive
Angle of wall friction	deg	Always positive
Vertical line surcharges	plf	Always positive, positive downward
Vertical distributed surcharges	psf	Always positive, positive downward
Water unit weight	pcf	Always positive
Earth and water pressures	psf	Positive to left
Shear force	lb/ft	Positive if acts to left on top end of vertical wall segment
Bending moment	lb-ft/ft	Positive if produces compression on left side of wall
Deflection	in.	Positive to left
Anchor force	lb/ft	Always tension

3 Example Solutions

3.1 Introduction

The example solutions shown in the following paragraphs are intended only to illustrate the operation of the program and are not to be construed as recommendations for the use of the program as a design aid.

Excerpts of the output data for the example solutions are presented. A complete tabulation of all results is too large for practical inclusion in this guide.

3.2 Soletanche Wall

The Soletanche wall is described in detail by Strom and Ebeling (2002). A schematic of the wall/soil system and the input file for CMULTIANC are shown in Figures 3-1 and 3-2, respectively.

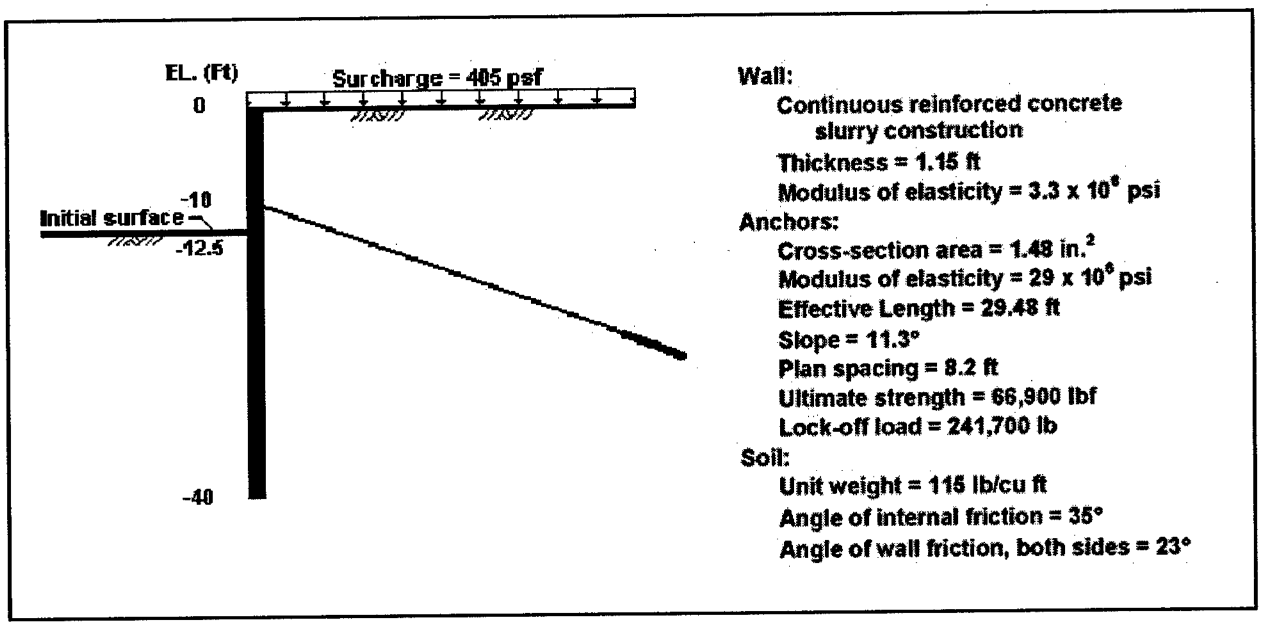


Figure 3-1. Soletanche wall

```
'SOLETANCHE WALL
WALL   0  3.300E+06    2628
WALL  -40
ANCHOR  -10    66900    241700    29000000    1.48    29.48
11.3     8.2
SOIL RIGHTSIDE  STRENGTHS   1
 0   115   115     0 35   23   23   .05   .5
SOIL LEFTSIDE  STRENGTHS   1
-12.5   115   115     0 35   23   23   .05   .5
VERTICAL UNIFORM   405
EXCAVATION DATA
-30
BOTTOM  FREE
FINISHED
```

Figure 3-2. Input file for Soletanche wall

After the input file is read and checked for errors, an echoprint of input data is generated in a temporary output file. The output file and various graphic presentations are available for viewing at any time. The echoprint of the input is shown in Figure 3-3.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                      WITH MULTIPLE LEVELS OF ANCHORS
     DATE: 3-DECEMBER-2002                                          TIME: 13:23:55

                                ****************
                                *  INPUT DATA  *
                                ****************

I.--HEADING
   'SOLETANCHE WALL

II.--WALL SEGMENT DATA

          ELEVATION
          AT TOP OF        MODULUS OF        MOMENT OF
           SEGMENT         ELASTICITY         INERTIA
            (FT)             (PSI)            (IN^4)
            0.00           3.300E+06          2628.00

          ELEVATION AT BOTTOM OF WALL =  -40.00

III.--ANCHOR DATA

               LOCK    ULTIMATE                  CROSS
   ELEV.        OFF    TENSILE   MODULUS OF    SECTION  EFFECTIVE              PLAN
  AT WALL      LOAD   STRENGTH   ELASTICITY     AREA     LENGTH     SLOPE    SPACING
   (FT)        (LB)     (LB)       (PSI)       (SQIN)     (FT)      (DEG)      (FT)
   -10.0    66900.0 241700.0    2.900E+07      1.48      29.48      11.3       8.2

IV.--SOIL LAYER DATA

       IV.A.1.--RIGHTSIDE PROPERTIES
                                            UNDRAINED  EFFECTIVE
                                            COHESIVE   INTERNAL
  LAYER TOP    <UNIT WEIGHT (PCF)>          STRENGTH   FRICTION    <WALL FRICT. (DEG)>
  ELEV. (FT)     SAT.          MOIST          (PSF)      (DEG)       ACTIVE     PASSIVE
     0.0        115.0          115.0           0.0        35.0        23.0       23.0

       IV.A.2.--RIGHTSIDE REFERENCE DISPLACEMENTS
          LAYER TOP       <REFERENCE DISPLACEMENT (IN)>
          ELEV. (FT)          ACTIVE          PASSIVE
             0.0               0.05             0.50
```

```
     IV.B.1.--LEFTSIDE PROPERTIES
                                           UNDRAINED  EFFECTIVE
                                           COHESIVE   INTERNAL
 LAYER TOP     <UNIT WEIGHT (PCF)>         STRENGTH   FRICTION     <WALL FRICT. (DEG)>
 ELEV. (FT)      SAT.        MOIST           (PSF)      (DEG)        ACTIVE     PASSIVE
   -12.5        115.0        115.0           0.0        35.0          23.0        23.0

     IV.A.2.--LEFTSIDE REFERENCE DISPLACEMENTS
       LAYER TOP       <REFERENCE DISPLACEMENT (IN)>
       ELEV. (FT)          ACTIVE        PASSIVE
         -12.5              0.05           0.50

V.--INITIAL WATER DATA
          NONE

VI.--VERTICAL SURCHARGE LOADS

     VI.A.--VERTICAL LINE LOADS
               NONE

     VI.B.--VERTICAL UNIFORM LOADS
                    RIGHTSIDE
                      (PSF)
                     405.00
     VI.C.--VERTICAL STRIP LOADS
               NONE

     VI.D.--VERTICAL RAMP LOADS
               NONE

     VI.E.--VERTICAL TRIANGULAR LOADS
               NONE

      VI.F.--VERTICAL VARIABLE LOADS
               NONE

VII.--EXCAVATION DATA
          EXCAVATION      WATER
          ELEVATION     ELEVATION
             (FT)          (FT)
            -30.00         NONE

VIII.--WALL BOTTOM CONDITIONS
          FREE
```

Figure 3-3. Echoprint of input data for Soletanche wall

When the solution process is initiated, CMULTIANC calculates the active and passive soil pressures and water pressures (if water is present) on each side of the wall for the initial soil (and water) profile. A tabulation of these pressures is appended to the output file. An excerpt of the pressure data is shown in Figure 3-4.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
               WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                   TIME: 13:24:06

                              ******************************
                              *      LIMIT PRESSURES       *
                              *   FOR INITIAL CONDITIONS   *
                              ******************************

       I.--HEADING

              'SOLETANCHE WALL

         RIGHTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
         AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS

          LEFTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
         AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS

    ELEV.   <--LEFTSIDE PRESSURES (PSF)->    <-RIGHTSIDE PRESSURES (PSF)->
    (FT)     WATER    PASSIVE      ACTIVE      WATER     ACTIVE    PASSIVE
     0.00    0.00       0.00        0.00        0.00      91.12    3385.80
    -1.00    0.00       0.00        0.00        0.00     117.00    4347.20
    -2.00    0.00       0.00        0.00        0.00     142.87    5308.60
    -3.00    0.00       0.00        0.00        0.00     168.75    6270.00
    -4.00    0.00       0.00        0.00        0.00     194.62    7231.40
    -5.00    0.00       0.00        0.00        0.00     220.50    8192.80
    -6.00    0.00       0.00        0.00        0.00     246.37    9154.20
    -7.00    0.00       0.00        0.00        0.00     272.25   10115.60
    -8.00    0.00       0.00        0.00        0.00     298.12   11077.00
    -9.00    0.00       0.00        0.00        0.00     324.00   12038.40
   -10.00    0.00       0.00        0.00        0.00     349.87   12999.80
   -11.00    0.00       0.00        0.00        0.00     375.75   13961.20
   -12.00    0.00       0.00        0.00        0.00     401.62   14922.60
   -12.50    0.00       0.00        0.00        0.00     414.56   15403.30
   -13.00    0.00     480.70       12.94        0.00     427.50   15884.00
   -14.00    0.00    1442.10       38.81        0.00     453.37   16845.40
      |        |         |           |           |          |         |
      |        |         |           |           |          |         |
   -31.00    0.00   17785.90      478.68        0.00     893.24   33189.20
   -32.00    0.00   18747.30      504.56        0.00     919.12   34150.60
   -33.00    0.00   19708.70      530.43        0.00     944.99   35112.00
   -34.00    0.00   20670.10      556.31        0.00     970.87   36073.40
   -35.00    0.00   21631.50      582.18        0.00     996.74   37034.80
   -36.00    0.00   22592.90      608.06        0.00    1022.62   37996.20
   -37.00    0.00   23554.30      633.93        0.00    1048.49   38957.60
   -38.00    0.00   24515.70      659.81        0.00    1074.37   39919.00
   -39.00    0.00   25477.10      685.68        0.00    1100.24   40880.40
   -40.00    0.00   26438.50      711.56        0.00    1126.12   41841.80
```

Figure 3-4. Initial limit pressures for Soletanche wall

A soon as initial limit soil pressures have been calculated, SSI curves for the initial conditions are evaluated and a tabulation of data defining the curves is appended to the output file. An excerpt of this tabulation is shown in Figure 3-5.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                    WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                   TIME: 13:24:06

                    ****************************************
                    *          INITIAL SSI CURVES          *
                    ****************************************

I.--HEADING
   'SOLETANCHE WALL

II.--RIGHT SIDE CURVES

  ELEV.     <---------ACTIVE--------->      <---------PASSIVE-------->
  (FT)      DISPL. (FT)     FORCE (LB)      DISPL. (FT)     FORCE (LB)
   0.00       0.004167         49.87         -0.041667        1853.13
  -1.00+      0.004167         54.19         -0.041667        2013.37
  -1.00-      0.004167         62.81         -0.041667        2333.83
  -2.00+      0.004167         67.12         -0.041667        2494.07
  -2.00-      0.004167         75.75         -0.041667        2814.53
  -3.00+      0.004167         80.06         -0.041667        2974.77
  -3.00-      0.004167         88.69         -0.041667        3295.23
  -4.00+      0.004167         93.00         -0.041667        3455.47
  -4.00-      0.004167        101.62         -0.041667        3775.93
  -5.00+      0.004167        105.94         -0.041667        3936.17
  -5.00-      0.004167        114.56         -0.041667        4256.63
    |            |               |               |               |
    |            |               |               |               |
 -36.00+      0.004167        507.00         -0.041667       18837.87
 -36.00-      0.004167        515.62         -0.041667       19158.33
 -37.00+      0.004167        519.93         -0.041667       19318.57
 -37.00-      0.004167        528.56         -0.041667       19639.03
 -38.00+      0.004167        532.87         -0.041667       19799.27
 -38.00-      0.004167        541.50         -0.041667       20119.73
 -39.00+      0.004167        545.81         -0.041667       20279.97
 -39.00-      0.004167        554.43         -0.041667       20600.43
 -40.00       0.004167        558.75         -0.041667       20760.67

III.--LEFT SIDE CURVES

  ELEV.     <--------PASSIVE--------->      <---------ACTIVE--------->
  (FT)      DISPL. (FT)     FORCE (LB)      DISPL. (FT)     FORCE (LB)
 -12.50       0.041667        -40.06         -0.004167          -1.08
 -13.00+      0.041667        -80.12         -0.004167          -2.16
 -13.00-      0.041667       -400.58         -0.004167         -10.78
 -14.00+      0.041667       -560.82         -0.004167         -15.09
 -14.00-      0.041667       -881.28         -0.004167         -23.72
 -15.00+      0.041667      -1041.52         -0.004167         -28.03
 -15.00-      0.041667      -1361.98         -0.004167         -36.66
    |            |               |               |               |
    |            |               |               |               |
 -36.00+      0.041667     -11136.22         -0.004167        -299.72
 -36.00-      0.041667     -11456.68         -0.004167        -308.34
 -37.00+      0.041667     -11616.92         -0.004167        -312.65
 -37.00-      0.041667     -11937.38         -0.004167        -321.28
 -38.00+      0.041667     -12097.62         -0.004167        -325.59
 -38.00-      0.041667     -12418.08         -0.004167        -334.22
 -39.00+      0.041667     -12578.32         -0.004167        -338.53
 -39.00-      0.041667     -12898.78         -0.004167        -347.15
 -40.00       0.041667     -13059.02         -0.004167        -351.47
```

Figure 3-5. Initial SSI curves for Soletanche wall

The next stage in the solution is to solve for displacements, bending moments, shear forces, and soil pressures throughout the wall using the initial SSI curves. A summary and complete tabulation of results for this solution are appended to the output file. The summary of results and an excerpt of the complete tabulation are shown in Figure 3-6.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEM
               WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                  TIME: 13:24:08

           *************************************************
           *        RESULTS FOR INITIAL SSI CURVES         *
           *************************************************

I.--HEADING
    'SOLETANCHE WALL

    SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
    AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS.

II.--MAXIMA

                                          MAXIMUM        MINIMUM
       DEFLECTION (FT)             :     9.249E-02      1.255E-03
            AT ELEVATION (FT)      :          0.00         -40.00

       BENDING MOMENT (LB-FT)      :     2.690E+04     -8.487E+02
            AT ELEVATION (FT)      :        -18.00         -32.00

       SHEAR (LB)                  :       3289.48       -3659.71
            AT ELEVATION (FT)      :        -13.00         -23.00


       RIGHTSIDE SOIL PRESSURE (PSF):      3712.40
            AT ELEVATION (FT)      :        -40.00

       LEFTSIDE SOIL PRESSURE (PSF) :      3755.00
            AT ELEVATION (FT)      :        -40.00

III.--ANCHOR FORCES

                                            TOTAL
          ELEVATION       ANCHOR           ANCHOR
          AT ANCHOR       STATUS            FORCE
             (FT)                           (LB)
           -10.00        INACTIVE

IV.--COMPLETE RESULTS

                             SHEAR        BENDING
ELEV.       DEFLECTION       FORCE        MOMENT       <-SOIL PRESS. (PSF)->
(FT)           (FT)          (LB)         (LB-FT)        LEFT          RIGHT
 0.00        9.249E-02        0.00          0.00          0.00          91.12
-1.00        8.712E-02      104.06         49.87          0.00         117.00
-2.00        8.175E-02      234.00        216.75          0.00         142.87
-3.00        7.638E-02      389.81        526.50          0.00         168.75
-4.00        7.102E-02      571.50       1004.99          0.00         194.62
-5.00        6.568E-02      779.06       1678.11          0.00         220.50
  |              |             |             |              |              |
  |              |             |             |              |              |
-35.00       1.430E-03      177.41       -478.77       3152.38        3148.74
-36.00       1.401E-03      162.59       -312.91       3278.91        3253.31
-37.00       1.368E-03      130.43       -172.66       3401.65        3363.39
-38.00       1.331E-03       89.01        -70.66       3521.47        3477.37
-39.00       1.293E-03       44.13        -12.76       3639.10        3593.96
-40.00       1.255E-03        0.00          0.00       3755.00        3712.40
```

Figure 3-6. Results for initial conditions for Soletanche wall

Following the solution for the initial SSI curves, the right-side curves are examined and any curve that has entered the active plateau is shifted so that the initial point at the active limit on the shifted curve occurs at the displacement of the wall at each location. A tabulation of the shifted curves is appended to the output file. An excerpt from the tabulation of shifted curves is shown in Figure 3-7.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                  WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                    TIME: 13:24:11

                 ****************************************
                 *          SHIFTED SSI CURVES          *
                 ****************************************

 I.--HEADING
      'SOLETANCHE WALL

 II.--RIGHT SIDE CURVES

   ELEV.     <---------ACTIVE--------->    <---------PASSIVE-------->
   (FT)      DISPL. (FT)    FORCE (LB)     DISPL. (FT)    FORCE (LB)
    0.00*     0.092490         49.87        0.046657        1853.13
   -1.00+*    0.087118         54.19        0.041285        2013.37
   -1.00-*    0.087118         62.81        0.041285        2333.83
   -2.00+*    0.081747         67.12        0.035914        2494.07
   -2.00-*    0.081747         75.75        0.035914        2814.53
   -3.00+*    0.076380         80.06        0.030547        2974.77
   -3.00-*    0.076380         88.69        0.030547        3295.23
   -4.00+*    0.071022         93.00        0.025189        3455.47
   -4.00-*    0.071022        101.62        0.025189        3775.93
   -5.00+*    0.065682        105.94        0.019848        3936.17
   -5.00-*    0.065682        114.56        0.019848        4256.63
      |           |              |              |               |
      |           |              |              |               |
  -19.00+*    0.006704        287.06       -0.039130       10665.97
  -19.00-*    0.006704        295.69       -0.039130       10986.43
  -20.00+*    0.005008        300.00       -0.040825       11146.67
  -20.00-*    0.005008        308.62       -0.040825       11467.13
  -21.00+     0.004167        312.94       -0.041667       11627.37
  -21.00-     0.004167        321.56       -0.041667       11947.83
  -22.00+     0.004167        325.87       -0.041667       12108.07
  -22.00-     0.004167        334.50       -0.041667       12428.53
      |           |              |              |               |
      |           |              |              |               |
  -38.00+     0.004167        532.87       -0.041667       19799.27
  -38.00-     0.004167        541.50       -0.041667       20119.73
  -39.00+     0.004167        545.81       -0.041667       20279.97
  -39.00-     0.004167        554.43       -0.041667       20600.43
  -40.00      0.004167        558.75       -0.041667       20760.67

            (Note:  * Indicates shifted curve.)
```

Figure 3-7. Shifted SSI curves for Soletanche wall

The solution is repeated using the shifted SSI curves, and a tabulation of results for this stage is appended to the output file. Because the displacements, bending moments, etc., using the shifted curves should be identical to the results for the initial conditions, this tabulation is not shown here.

The construction sequence begins with the installation of the topmost anchor. Anchor installation begins with application of a concentrated load, equal to the horizontal component of the anchor lock-off load, at the anchor attachment point. A summary of results and complete results are appended to the output file. The summary of results for this step is shown in Figure 3-8.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                      WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                     TIME: 13:24:18

               **************************************************
               *  RESULTS AFTER ANCHOR LOCK OFF LOAD AT EL -10 *
               **************************************************

I.--HEADING
   'SOLETANCHE WALL

II.--MAXIMA

                                              MAXIMUM         MINIMUM
       DEFLECTION (FT)                 :     9.225E-02       1.252E-03
            AT ELEVATION (FT)          :          0.00          -40.00

       BENDING MOMENT (LB-FT)          :     2.382E+04      -7.220E+02
            AT ELEVATION (FT)          :        -18.00          -32.00

       SHEAR (LB)                      :       5768.59        -3262.77
            AT ELEVATION (FT)          :        -10.00          -23.00


       RIGHTSIDE SOIL PRESSURE (PSF):          3714.95
            AT ELEVATION (FT)          :        -40.00

       LEFTSIDE SOIL PRESSURE (PSF)    :       3753.38
            AT ELEVATION (FT)          :        -40.00

   III.--ANCHOR FORCES

                                   TOTAL
      ELEVATION     ANCHOR        ANCHOR
      AT ANCHOR     STATUS         FORCE
         (FT)                      (LB)
        -10.00     INACTIVE
```

Figure 3-8. Summary of results after anchor lock-off load for Soletanche wall

The next stage in anchor installation involves replacing the anchor lock-off load with a nonlinear concentrated spring. Defining points on the curve for the anchor spring are established so that the force in the anchor spring is equal to the lock-off load at the displacement of the anchor attachment point. The solution is repeated with the anchor spring in place. The results for displacements, bending moments, etc., should be identical to those for the lock-off load solution. A tabulation of a summary of results and complete results are appended to the output file. The summary of results for this step is shown in Figure 3-9.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                    WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                    TIME: 13:24:18

                  **************************************************
                  *  RESULTS AFTER ANCHOR INSTALLATION AT EL -10   *
                  **************************************************

I.--HEADING
   'SOLETANCHE WALL

II.--MAXIMA

                                            MAXIMUM        MINIMUM
   DEFLECTION (FT)                   :     9.225E-02      1.252E-03
        AT ELEVATION (FT)            :          0.00         -40.00

   BENDING MOMENT (LB-FT)            :     2.382E+04     -7.220E+02
        AT ELEVATION (FT)            :        -18.00         -32.00

   SHEAR (LB)                        :       5768.59       -3262.77
        AT ELEVATION (FT)            :        -10.00         -23.00


   RIGHTSIDE SOIL PRESSURE (PSF):            3714.95
        AT ELEVATION (FT)            :        -40.00

   LEFTSIDE SOIL PRESSURE (PSF) :            3753.38
        AT ELEVATION (FT)            :        -40.00

III.--ANCHOR FORCES

                                       TOTAL
      ELEVATION        ANCHOR         ANCHOR
      AT ANCHOR        STATUS         FORCE*
        (FT)                           (LB)
       -10.00          ACTIVE         66900
                                      * ALONG ANCHOR LINE OF ACTION
```

Figure 3-9. Summary of results for anchor spring replacing lock-off load for Soletanche wall

The next stage in the solution is excavation on the left side to elevation –30. The soil between the initial left-side surface, elevation –12.5, and elevation –30 is removed and the left-side soil pressures and SSI curves are recalculated. (Note: The soil pressures and SSI curves are unchanged during this stage.) Tabulations of the left-side soil pressures, SSI curves, and the summary of results from the solution for the revised left-side profile are shown in Figures 3-10, 3-11, and 3-12, respectively.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                  WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                    TIME: 13:24:21

                     ******************************
                     *      LIMIT PRESSURES       *
                     *  AFTER EXCAVATE TO EL -30  *
                     ******************************

I.--HEADING
   'SOLETANCHE WALL

     RIGHTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
     AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS
```

LEFTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS

ELEV.	<--LEFTSIDE PRESSURES	(PSF)->		<-RIGHTSIDE PRESSURES	(PSF)->	
(FT)	WATER	PASSIVE	ACTIVE	WATER	ACTIVE	PASSIVE
-30.00	0.00	0.00	0.00	0.00	867.37	32227.80
-31.00	0.00	961.40	25.87	0.00	893.24	33189.20
-32.00	0.00	1922.80	51.75	0.00	919.12	34150.60
-33.00	0.00	2884.20	77.62	0.00	944.99	35112.00
-34.00	0.00	3845.60	103.50	0.00	970.87	36073.40
-35.00	0.00	4807.00	129.37	0.00	996.74	37034.80
-36.00	0.00	5768.40	155.25	0.00	1022.62	37996.20
-37.00	0.00	6729.80	181.12	0.00	1048.49	38957.60
-38.00	0.00	7691.20	207.00	0.00	1074.37	39919.00
-39.00	0.00	8652.60	232.87	0.00	1100.24	40880.40
-40.00	0.00	9614.00	258.75	0.00	1126.12	41841.80

Figure 3-10. Limit pressures after excavation to elevation –30 for Soletanche wall

CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002 TIME: 13:24:21

****
* SSI CURVES AFTER EXCAVATE TO EL -30 *
****

I.--HEADING
'SOLETANCHE WALL

III.--LEFT SIDE CURVES

ELEV.	<--------PASSIVE	--------->	<---------ACTIVE	--------->
(FT)	DISPL. (FT)	FORCE (LB)	DISPL. (FT)	FORCE (LB)
-30.00	0.041667	-160.23	-0.004167	-4.31
-31.00+	0.041667	-320.47	-0.004167	-8.62
-31.00-	0.041667	-640.93	-0.004167	-17.25
-32.00+	0.041667	-801.17	-0.004167	-21.56
-32.00-	0.041667	-1121.63	-0.004167	-30.19
-33.00+	0.041667	-1281.87	-0.004167	-34.50
-33.00-	0.041667	-1602.33	-0.004167	-43.12
-34.00+	0.041667	-1762.57	-0.004167	-47.44
-34.00-	0.041667	-2083.03	-0.004167	-56.06
-35.00+	0.041667	-2243.27	-0.004167	-60.37
-35.00-	0.041667	-2563.73	-0.004167	-69.00
-36.00+	0.041667	-2723.97	-0.004167	-73.31
-36.00-	0.041667	-3044.43	-0.004167	-81.94
-37.00+	0.041667	-3204.67	-0.004167	-86.25
-37.00-	0.041667	-3525.13	-0.004167	-94.87
-38.00+	0.041667	-3685.37	-0.004167	-99.19
-38.00-	0.041667	-4005.83	-0.004167	-107.81
-39.00+	0.041667	-4166.07	-0.004167	-112.12
-39.00-	0.041667	-4486.53	-0.004167	-120.75
-40.00	0.041667	-4646.77	-0.004167	-125.06

Figure 3-11. Left-side SSI curves after excavation to elevation –30 for Soletanche wall

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                     WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                      TIME: 13:24:21

          **************************************************
          *      RESULTS AFTER EXCAVATE TO EL -30        *
          **************************************************

I.--HEADING
   'SOLETANCHE WALL

II.--MAXIMA

                                            MAXIMUM          MINIMUM
      DEFLECTION (FT)              :       8.029E-02       -8.980E-04
           AT ELEVATION (FT)       :            0.00           -40.00

      BENDING MOMENT (LB-FT)       :       3.061E+04       -2.655E+04
           AT ELEVATION (FT)       :          -10.00           -24.00

      SHEAR (LB)                   :         5234.02         -7377.64
           AT ELEVATION (FT)       :          -31.00           -10.00


      RIGHTSIDE SOIL PRESSURE (PSF):         5625.27
           AT ELEVATION (FT)       :          -40.00

      LEFTSIDE SOIL PRESSURE (PSF) :         2479.90
           AT ELEVATION (FT)       :          -35.00

III.--ANCHOR FORCES

                                     TOTAL
          ELEVATION      ANCHOR     ANCHOR
          AT ANCHOR      STATUS     FORCE*
             (FT)                    (LB)
           -10.00        ACTIVE     101551
                                    * ALONG ANCHOR LINE OF ACTION
```

Figure 3-12. Summary of results after excavation to elevation –30 for Soletanche wall

As the solution progresses, maximum effects for each stage are displayed in a maxima summary file. The final maxima summary for the Soletanche wall is shown in Figure 3-13.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                  WITH MULTIPLE LEVELS OF ANCHORS
DATE: 3-DECEMBER-2002                                      TIME: 13:24:08

             ****************************************
             *  SUMMARY OF MAXIMA STAGE-BY-STAGE  *
             ****************************************

I.--HEADING
   'SOLETANCHE WALL

II.--MAXIMA

      STAGE                    :       INITIAL PROFILES

                                      MAXIMUM          MINIMUM
      DEFLECTION (FT)          :     9.249E-02        1.255E-03
           AT ELEVATION (FT):             0.00           -40.00
      BENDING MOMENT (LB-FT):        2.690E+04       -8.487E+02
```

```
    AT ELEVATION (FT):          -18.00        -32.00

STAGE                     :     AFTER ANCHOR INSTALLATION AT EL. -10 (FT)

                                 MAXIMUM        MINIMUM
DEFLECTION (FT)           :    9.225E-02      1.252E-03
    AT ELEVATION (FT):             0.00         -40.00
BENDING MOMENT (LB-FT):        2.382E+04     -7.220E+02
    AT ELEVATION (FT):           -18.00         -32.00

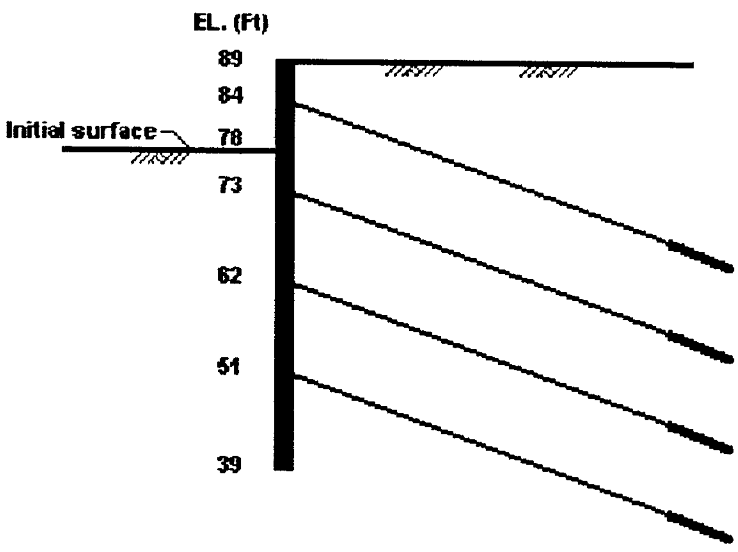
STAGE                     :     AFTER EXCAVATION TO EL. -30 (FT)

                                 MAXIMUM        MINIMUM
DEFLECTION (FT)           :    8.029E-02     -8.980E-04
    AT ELEVATION (FT):             0.00         -40.00
BENDING MOMENT (LB-FT):        3.061E+04     -2.655E+04
    AT ELEVATION (FT):           -10.00         -24.00
```

Figure 3-13. Maxima summary for Soletanche wall

3.3 Bonneville Type Wall

Figure 3-14 is a simulation of the temporary tieback wall for the Bonneville Navigation Lock described by Strom and Ebeling (2002) and Munger et al. (1991).



Wall:

Continuous reinforced concrete slurry construction

Thickness = 3 ft

Modulus of elasticity = 3.3 x 10^6 psi

Anchors:

Cross-section area = 1.519 in.^{2}

Modulus of elasticity = 29 x 10^6 psi

Effective Length = 55 ft

Slope = 20°

Plan spacing = 12 ft

Ultimate strength = 436,500 lbf

Lock-off load = 35,880 lb

Soil:

Unit weight = 125 lb/cu ft

Angle of internal friction = 30°

Angle of wall friction:

right side = 0

left side = 15°

Figure 3-14. Bonneville type wall simulation

The soil surface on the left side shown in Figure 3-14 is consistent with the first excavation after the concrete wall is in place and before the top anchor is installed. Subsequent excavations in the solution are assumed to be to 6 ft below the level of the corresponding anchor (viz.: Elevations 67, 56, 45, and 40 ft). The bottom of the wall is assumed to be keyed into competent rock to prevent lateral deflection but to allow unrestrained rotation.

The input data file for this example is shown in Figure 3-15.

```
'BONNEVILLE TIEBACK WALL
WALL    89   3.300E+06    46656
WALL    39
ANCHOR    84    358800    436500    29000000    1.519    55    20    12
ANCHOR    73    358800    436500    29000000    1.519    55    20    12
ANCHOR    62    358800    436500    29000000    1.519    55    20    12
ANCHOR    51    358800    436500    29000000    1.519    55    20    12
SOIL RIGHTSIDE   STRENGTHS    1
 89    125    125      0 30    0    15    .05    .5
SOIL LEFTSIDE   STRENGTHS    1
 78    125    125      0 30    0    15    .05    .5
VERTICAL UNIFORM    875
EXCAVATION DATA
 67
 56
 45
 40
BOTTOM  PINNED
FINISHED
```

Figure 3-15. Input file for Bonneville wall

The echoprint of input data generated by CMULTIANC is shown in Figure 3-16.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                   WITH MULTIPLE LEVELS OF ANCHORS
DATE: 6-NOVEMBER-2002                                    TIME: 15:30:49

                         ****************
                         *  INPUT DATA  *
                         ****************

I.--HEADING
   'BONNEVILLE TIEBACK WALL

II.--WALL SEGMENT DATA

      ELEVATION
      AT TOP OF        MODULUS OF        MOMENT OF
       SEGMENT         ELASTICITY         INERTIA
        (FT)             (PSI)            (IN^4)
        89.00          3.300E+06         46656.00

      ELEVATION AT BOTTOM OF WALL = 39.00

III.--ANCHOR DATA

           LOCK    ULTIMATE                     CROSS
 ELEV.      OFF    TENSILE    MODULUS OF      SECTION   EFFECTIVE              PLAN
AT WALL    LOAD    STRENGTH   ELASTICITY       AREA      LENGTH      SLOPE    SPACING
 (FT)      (LB)      (LB)        (PSI)        (SQIN)      (FT)       (DEG)     (FT)
  84.0 358800.0 436500.0    2.900E+07         1.52       55.00       20.0      12.0
  73.0 358800.0 436500.0    2.900E+07         1.52       55.00       20.0      12.0
  62.0 358800.0 436500.0    2.900E+07         1.52       55.00       20.0      12.0
  51.0 358800.0 436500.0    2.900E+07         1.52       55.00       20.0      12.0
```

```
IV.--SOIL LAYER DATA

                IV.A.1.--RIGHTSIDE PROPERTIES
                                          UNDRAINED  EFFECTIVE
                                          COHESIVE   INTERNAL
LAYER TOP   <UNIT WEIGHT (PCF)>           STRENGTH   FRICTION    <WALL FRICT. (DEG)>
ELEV. (FT)   SAT.          MOIST            (PSF)      (DEG)       ACTIVE    PASSIVE
   89.0     125.0          125.0             0.0        30.0        0.0        15.0

        IV.A.2.--RIGHTSIDE REFERENCE DISPLACEMENTS
            LAYER TOP        <REFERENCE DISPLACEMENT (IN)>
            ELEV. (FT)           ACTIVE         PASSIVE
               89.0               0.05           0.50

                IV.B.1.--LEFTSIDE PROPERTIES
                                          UNDRAINED  EFFECTIVE
                                          COHESIVE   INTERNAL
LAYER TOP   <UNIT WEIGHT (PCF)>           STRENGTH   FRICTION    <WALL FRICT. (DEG)>
ELEV. (FT)   SAT.          MOIST            (PSF)      (DEG)       ACTIVE    PASSIVE
   78.0     125.0          125.0             0.0        30.0        0.0        15.0

                IV.A.2.--LEFTSIDE REFERENCE DISPLACEMENTS
            LAYER TOP        <REFERENCE DISPLACEMENT (IN)>
            ELEV. (FT)           ACTIVE         PASSIVE
               78.0               0.05           0.50

V.--INITIAL WATER DATA
      NONE

VI.--VERTICAL SURCHARGE LOADS

    VI.A.--VERTICAL LINE LOADS
           NONE

    VI.B.--VERTICAL UNIFORM LOADS
             RIGHTSIDE
               (PSF)
              875.00

    VI.C.--VERTICAL STRIP LOADS
        NONE

    VI.D.--VERTICAL RAMP LOADS
        NONE

    VI.E.--VERTICAL TRIANGULAR LOADS
        NONE

    VI.F.--VERTICAL VARIABLE LOADS
        NONE

VII.--EXCAVATION DATA
      EXCAVATION       WATER
      ELEVATION      ELEVATION
         (FT)           (FT)
        67.00          NONE
        56.00          NONE
        45.00          NONE
        40.00          NONE

VII.--WALL BOTTOM CONDITIONS
      PINNED
```

Figure 3-16. Echoprint of input data for Bonneville wall

The maxima summary for the solution is shown in Figure 3-17.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                    WITH MULTIPLE LEVELS OF ANCHORS
DATE: 6-NOVEMBER-2002                                  TIME: 15:31:00

                ****************************************
                *  SUMMARY OF MAXIMA STAGE-BY-STAGE   *
                ****************************************

I.--HEADING
   'BONNEVILLE TIEBACK WALL

II.--MAXIMA

       STAGE                    :        INITIAL PROFILES

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       4.136E-02      0.000E+00
           AT ELEVATION (FT):             89.00          39.00
      BENDING MOMENT (LB-FT):           8.366E+04     -1.063E+04
           AT ELEVATION (FT):             66.00          43.00

      STAGE                     :       AFTER ANCHOR INSTALLATION AT EL.  84 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       2.225E-02      0.000E+00
           AT ELEVATION (FT):             89.00          39.00
      BENDING MOMENT (LB-FT):           4.588E+04     -2.712E+04
           AT ELEVATION (FT):             61.00          77.00

      STAGE                     :       AFTER EXCAVATION TO EL.  67 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       2.167E-02      0.000E+00
           AT ELEVATION (FT):             78.00          39.00
      BENDING MOMENT (LB-FT):           2.782E+04     -6.361E+04
           AT ELEVATION (FT):             51.00          71.00

      STAGE                     :       AFTER ANCHOR INSTALLATION AT EL.  73 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       1.901E-02      0.000E+00
           AT ELEVATION (FT):             89.00          39.00
      BENDING MOMENT (LB-FT):           4.367E+04     -1.269E+04
           AT ELEVATION (FT):             73.00          43.00

      STAGE                     :       AFTER EXCAVATION TO EL.  56 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       2.401E-02      0.000E+00
           AT ELEVATION (FT):             62.00          39.00
      BENDING MOMENT (LB-FT):           4.089E+04     -1.217E+05
           AT ELEVATION (FT):             73.00          58.00

      STAGE                     :       AFTER ANCHOR INSTALLATION AT EL.  62 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       1.961E-02      0.000E+00
           AT ELEVATION (FT):             89.00          39.00
      BENDING MOMENT (LB-FT):           6.261E+04     -5.209E+04
           AT ELEVATION (FT):             62.00          48.00

      STAGE                     :       AFTER EXCAVATION TO EL.  45 (FT)

                                         MAXIMUM        MINIMUM
      DEFLECTION (FT)           :       1.817E-02      0.000E+00
           AT ELEVATION (FT):             89.00          39.00
      BENDING MOMENT (LB-FT):           6.104E+04     -1.043E+05
           AT ELEVATION (FT):             73.00          49.00


      STAGE                     :       AFTER ANCHOR INSTALLATION AT EL.  51 (FT)
```

```
                                  MAXIMUM         MINIMUM
DEFLECTION (FT)          :       2.046E-02       0.000E+00
     AT ELEVATION (FT):              89.00           39.00
BENDING MOMENT (LB-FT):          6.725E+04      -5.372E+04
     AT ELEVATION (FT):              62.00           44.00

STAGE                    :        AFTER EXCAVATION TO EL.  40 (FT)

                                  MAXIMUM         MINIMUM
DEFLECTION (FT)          :       2.045E-02       0.000E+00
     AT ELEVATION (FT):              89.00           39.00
BENDING MOMENT (LB-FT):          6.746E+04      -5.565E+04
     AT ELEVATION (FT):              62.00           44.00
```

Figure 3-17. Maxima summary for Bonneville wall

3.4 Cacoilo Wall

A sheet-pile wall in a soil profile composed of both cohesionless and cohesive soils is summarized by Cacoilo et al. (1998). The reference does not provide the characteristics of the sheet pile; hence, for this example the sheet pile is assumed to be a PZ 38 section. A schematic of the system is shown in Figure 3-18.

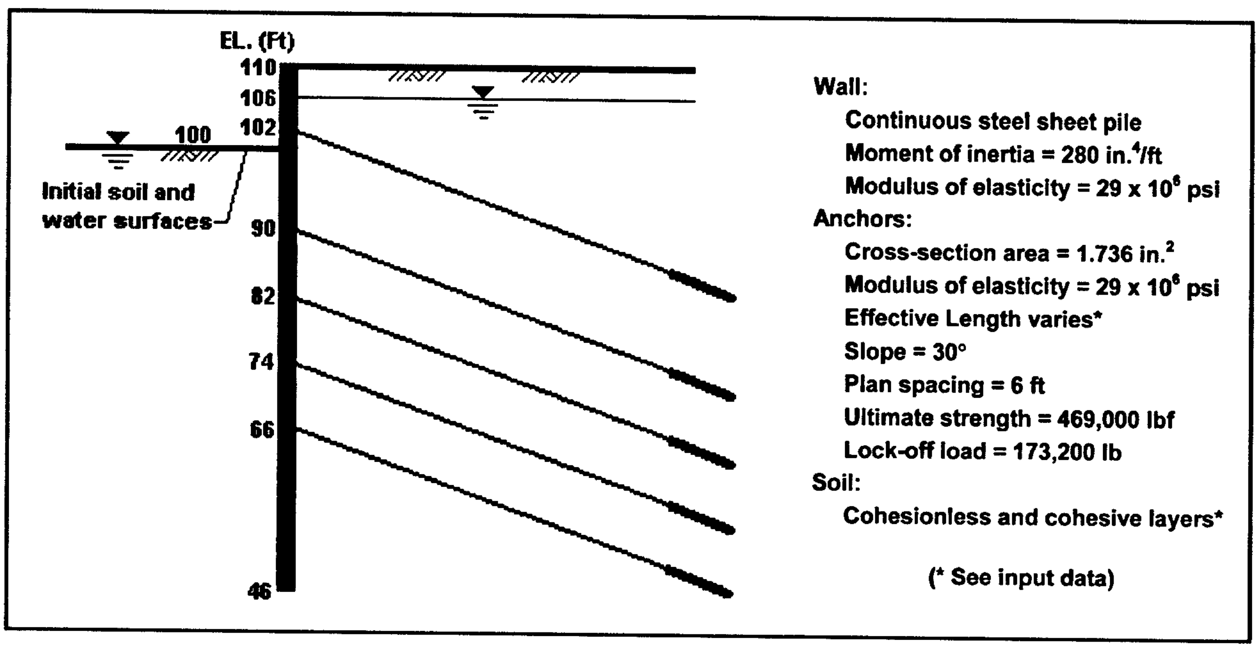


Figure 3-18. Cacoilo wall

The assumed wall stiffness results in a minimum value of EI/L^4 equal to 2.72, which does not conform to the "stiff" wall condition on which CMULTIANC is based. This example is included here to illustrate the treatment of water pressures and cohesive soils employed in the program.

It also assumed that the water on the left side is dewatered to the level of the soil surface on the left side at each excavation stage.

The input data file for the Cacoilo wall is shown in Figure 3-19.

```
'CACOILO WALL
WALL   110  2.900E+07    280
WALL   46
ANCHOR   102    173205    469039    29000000   1.736   105   30    6
ANCHOR   90   173205    469039    29000000   1.736   82   30    6
ANCHOR   82   173205    469039    29000000   1.736   56   30    6
ANCHOR   74   173205    469039    29000000   1.736   39   30    6
ANCHOR   66   173205    469039    29000000   1.736   39   30    6
SOIL RIGHTSIDE   STRENGTHS    4
110    120    100      0 30    0    0    .05    .5
80    115    115     300 0    0    0    .2    1
74    110    110     700 0    0    0    .2    1
68    120    120     2000 0    0    0    .2    1
SOIL LEFTSIDE   STRENGTHS    4
100    120    100      0 30    0    0    .05    .5
80    115    115     300 0    0    0    .2    1
74    110    110     700 0    0    0    .2    1
68    120    120     2000 0    0    0    .2    1
WATER ELEVATIONS    62.5    106    100
EXCAVATION DATA
 88    88
 80    80
 72    72
 64    64
 58    58
BOTTOM   FREE
FINISHED
```

Figure 3-19. Input file for Cacoilo wall

The echoprint of input data is shown in Figure 3-20.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                    WITH MULTIPLE LEVELS OF ANCHORS
DATE: 9-DECEMBER-2002                                    TIME: 14:28:11

                          ****************
                          *  INPUT DATA  *
                          ****************

I.--HEADING
   'CACOILO WALL

II.--WALL SEGMENT DATA

      ELEVATION
      AT TOP OF        MODULUS OF        MOMENT OF
       SEGMENT         ELASTICITY         INERTIA
        (FT)             (PSI)            (IN^4)
       110.00          2.900E+07          280.00

      ELEVATION AT BOTTOM OF WALL =  46.00

III.--ANCHOR DATA
```

ELEV. AT WALL (FT)	LOCK OFF LOAD (LB)	ULTIMATE TENSILE STRENGTH (LB)	MODULUS OF ELASTICITY (PSI)	CROSS SECTION AREA (SQIN)	EFFECTIVE LENGTH (FT)	SLOPE (DEG)	PLAN SPACING (FT)
102.0	173205.0	469039.0	2.900E+07	1.74	105.00	30.0	6.0
90.0	173205.0	469039.0	2.900E+07	1.74	82.00	30.0	6.0
82.0	173205.0	469039.0	2.900E+07	1.74	56.00	30.0	6.0
74.0	173205.0	469039.0	2.900E+07	1.74	39.00	30.0	6.0
66.0	173205.0	469039.0	2.900E+07	1.74	39.00	30.0	6.0

IV.--SOIL LAYER DATA

IV.A.1.--RIGHTSIDE PROPERTIES

LAYER TOP ELEV. (FT)	<UNIT WEIGHT (PCF)> SAT.	MOIST	UNDRAINED COHESIVE STRENGTH (PSF)	EFFECTIVE INTERNAL FRICTION (DEG)	<WALL FRICT. (DEG)> ACTIVE	PASSIVE
110.0	120.0	100.0	0.0	30.0	0.0	0.0
80.0	115.0	115.0	300.0	0.0	0.0	0.0
74.0	110.0	110.0	700.0	0.0	0.0	0.0
68.0	120.0	120.0	2000.0	0.0	0.0	0.0

IV.A.2.--RIGHTSIDE REFERENCE DISPLACEMENTS

LAYER TOP ELEV. (FT)	<REFERENCE DISPLACEMENT (IN)> ACTIVE	PASSIVE
110.0	0.05	0.50
80.0	0.20	1.00
74.0	0.20	1.00
68.0	0.20	1.00

IV.B.1.--LEFTSIDE PROPERTIES

LAYER TOP ELEV. (FT)	<UNIT WEIGHT (PCF)> SAT.	MOIST	UNDRAINED COHESIVE STRENGTH (PSF)	EFFECTIVE INTERNAL FRICTION (DEG)	<WALL FRICT. (DEG)> ACTIVE	PASSIVE
100.0	120.0	100.0	0.0	30.0	0.0	0.0
80.0	115.0	115.0	300.0	0.0	0.0	0.0
74.0	110.0	110.0	700.0	0.0	0.0	0.0
68.0	120.0	120.0	2000.0	0.0	0.0	0.0

IV.A.2.--LEFTSIDE REFERENCE DISPLACEMENTS

LAYER TOP ELEV. (FT)	<REFERENCE DISPLACEMENT (IN)> ACTIVE	PASSIVE
100.0	0.05	0.50
80.0	0.20	1.00
74.0	0.20	1.00
68.0	0.20	1.00

V.--INITIAL WATER DATA

UNIT WEIGHT = 62.50 (PCF)
RIGHTSIDE ELEVATION = 106.00 (FT)
LEFTSIDE ELEVATION = 100.00 (FT)

VI.--VERTICAL SURCHARGE LOADS

NONE

VIII.--EXCAVATION DATA

EXCAVATION ELEVATION (FT)	WATER ELEVATION (FT)
88.00	88.00
80.00	80.00
72.00	72.00
64.00	64.00
58.00	58.00

VII.--WALL BOTTOM CONDITIONS

FREE

Figure 3-20. Echoprint of input data for Cacoilo wall

The soil and water pressures calculated by the program for the initial soil profile are shown in Figure 3-21.

```
CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                   WITH MULTIPLE LEVELS OF ANCHORS
DATE: 9-DECEMBER-2002                                   TIME: 14:28:31

                  ******************************
                  *      LIMIT PRESSURES       *
                  *   FOR INITIAL CONDITIONS   *
                  ******************************

I.--HEADING
   'CACOILO WALL

      RIGHTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
      AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS

       LEFTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
      AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS

 ELEV.   <--LEFTSIDE PRESSURES (PSF)->    <-RIGHTSIDE PRESSURES (PSF)->
 (FT)     WATER    PASSIVE      ACTIVE     WATER      ACTIVE    PASSIVE
110.00     0.00       0.00        0.00      0.00        0.00       0.00
109.00     0.00       0.00        0.00      0.00       33.33     300.00
108.00     0.00       0.00        0.00      0.00       66.67     600.00
107.00     0.00       0.00        0.00      0.00      100.00     900.00
106.00     0.00       0.00        0.00      0.00      133.33    1200.00
105.00     0.00       0.00        0.00     62.50      152.50    1372.50
104.00     0.00       0.00        0.00    125.00      171.67    1545.00
103.00     0.00       0.00        0.00    187.50      190.83    1717.50
102.00     0.00       0.00        0.00    250.00      210.00    1890.00
101.00     0.00       0.00        0.00    312.50      229.17    2062.50
100.00     0.00       0.00        0.00    375.00      248.33    2235.00
 99.00    62.50     172.50       19.17    437.50      267.50    2407.50
 98.00   125.00     345.00       38.33    500.00      286.67    2580.00
 97.00   187.50     517.50       57.50    562.50      305.83    2752.50
 96.00   250.00     690.00       76.67    625.00      325.00    2925.00
 95.00   312.50     862.50       95.83    687.50      344.17    3097.50
 94.00   375.00    1035.00      115.00    750.00      363.33    3270.00
 93.00   437.50    1207.50      134.17    812.50      382.50    3442.50
 92.00   500.00    1380.00      153.33    875.00      401.67    3615.00
 91.00   562.50    1552.50      172.50    937.50      420.83    3787.50
 90.00   625.00    1725.00      191.67   1000.00      440.00    3960.00
 89.00   687.50    1897.50      210.83   1062.50      459.17    4132.50
 88.00   750.00    2070.00      230.00   1125.00      478.33    4305.00
 87.00   812.50    2242.50      249.17   1187.50      497.50    4477.50
 86.00   875.00    2415.00      268.33   1250.00      516.67    4650.00
 85.00   937.50    2587.50      287.50   1312.50      535.83    4822.50
 84.00  1000.00    2760.00      306.67   1375.00      555.00    4995.00
 83.00  1062.50    2932.50      325.83   1437.50      574.17    5167.50
 82.00  1125.00    3105.00      345.00   1500.00      593.33    5340.00
 81.00  1187.50    3277.50      364.17   1562.50      612.50    5512.50
 80.00+ 1250.00    3450.00      383.33   1625.00      631.67    5685.00
 80.00-    0.00    3000.00     1800.00      0.00     2920.00    4120.00
 79.00     0.00    3115.00     1915.00      0.00     3035.00    4235.00
 78.00     0.00    3230.00     2030.00      0.00     3150.00    4350.00
 77.00     0.00    3345.00     2145.00      0.00     3265.00    4465.00
 76.00     0.00    3460.00     2260.00      0.00     3380.00    4580.00
 75.00     0.00    3575.00     2375.00      0.00     3495.00    4695.00
 74.78     0.00    3600.00     2400.00      0.00     3520.00    4720.00
 74.00+    0.00    3690.00     2490.00      0.00     3610.00    4810.00
 74.00-    0.00    4490.00     1690.00      0.00     2810.00    5610.00
 73.00     0.00    4600.00     1800.00      0.00     2920.00    5720.00
 72.00     0.00    4710.00     1910.00      0.00     3030.00    5830.00
 71.00     0.00    4820.00     2020.00      0.00     3140.00    5940.00
 70.00     0.00    4930.00     2130.00      0.00     3250.00    6050.00
 69.00     0.00    5040.00     2240.00      0.00     3360.00    6160.00
 68.00+    0.00    5150.00     2350.00      0.00     3470.00    6270.00
```

68.00-	0.00	7750.00	0.00	0.00	870.00	8870.00
67.00	0.00	7870.00	0.00	0.00	990.00	8990.00
66.00	0.00	7990.00	0.00	0.00	1110.00	9110.00
65.92	0.00	8000.00	0.00	0.00	1120.00	9120.00
65.00	0.00	8110.00	110.00	0.00	1230.00	9230.00
64.00	0.00	8230.00	230.00	0.00	1350.00	9350.00
63.00	0.00	8350.00	350.00	0.00	1470.00	9470.00
62.00	0.00	8470.00	470.00	0.00	1590.00	9590.00
61.00	0.00	8590.00	590.00	0.00	1710.00	9710.00
60.00	0.00	8710.00	710.00	0.00	1830.00	9830.00
59.00	0.00	8830.00	830.00	0.00	1950.00	9950.00
58.00	0.00	8950.00	950.00	0.00	2070.00	10070.00
57.00	0.00	9070.00	1070.00	0.00	2190.00	10190.00
56.00	0.00	9190.00	1190.00	0.00	2310.00	10310.00
55.00	0.00	9310.00	1310.00	0.00	2430.00	10430.00
54.00	0.00	9430.00	1430.00	0.00	2550.00	10550.00
53.92	0.00	9440.00	1440.00	0.00	2560.00	10560.00
53.00	0.00	9550.00	1550.00	0.00	2670.00	10670.00
52.00	0.00	9670.00	1670.00	0.00	2790.00	10790.00
51.00	0.00	9790.00	1790.00	0.00	2910.00	10910.00
50.00	0.00	9910.00	1910.00	0.00	3030.00	11030.00
49.00	0.00	10030.00	2030.00	0.00	3150.00	11150.00
48.00	0.00	10150.00	2150.00	0.00	3270.00	11270.00
47.00	0.00	10270.00	2270.00	0.00	3390.00	11390.00
46.00	0.00	10390.00	2390.00	0.00	3510.00	11510.00

Figure 3-21. Initial water and soil limit pressures for initial conditions

Note that the water pressures are set to zero below elevation 80, the top of the cohesive layers in the profile. The effects of water in the cohesive layers are included in the limiting active and passive soil pressures. Note also that the active pressures at some elevations in the cohesive layers are zero.

The maxima summary for the solution of this system is shown in Figure 3-22.

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CMULTIANC: SIMULATION OF CONSTRUCTION SEQUENCE FOR STIFF WALL SYSTEMS
                WITH MULTIPLE LEVELS OF ANCHORS
DATE: 9-DECEMBER-2002                                     TIME: 14:28:34

              **************************************
              *  SUMMARY OF MAXIMA STAGE-BY-STAGE  *
              **************************************

I.--HEADING
   'CACOILO WALL

II.--MAXIMA

     STAGE                    :      INITIAL PROFILES

                                      MAXIMUM       MINIMUM
     DEFLECTION (FT)          :      2.297E-01     6.753E-03
         AT ELEVATION (FT):             110.00         53.00
     BENDING MOMENT (LB-FT):         3.891E+04    -4.996E+03
         AT ELEVATION (FT):              89.00         73.00

     STAGE                    :      AFTER ANCHOR INSTALLATION AT EL.  102 (FT)

                                      MAXIMUM       MINIMUM
     DEFLECTION (FT)          :      6.418E-02     6.614E-03
         AT ELEVATION (FT):             110.00         55.00
     BENDING MOMENT (LB-FT):         2.491E+04    -2.470E+04
         AT ELEVATION (FT):             102.00         96.00

     STAGE                    :      AFTER EXCAVATION TO EL.  88 (FT)
```

```
                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     2.987E-01     -6.496E-02
     AT ELEVATION (FT):        86.00         110.00
BENDING MOMENT (LB-FT):      8.332E+04     -1.138E+05
     AT ELEVATION (FT):        65.00          87.00

STAGE                  :     AFTER ANCHOR INSTALLATION AT EL.  90 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     8.698E-02      1.274E-02
     AT ELEVATION (FT):        80.00          56.00
BENDING MOMENT (LB-FT):      3.115E+04     -4.093E+04
     AT ELEVATION (FT):        64.00          78.00

STAGE                  :     AFTER EXCAVATION TO EL.  80 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     1.860E-01     -4.708E-02
     AT ELEVATION (FT):        80.00         110.00
BENDING MOMENT (LB-FT):      5.987E+04     -9.445E+04
     AT ELEVATION (FT):        63.00          79.00

STAGE                  :     AFTER ANCHOR INSTALLATION AT EL.  82 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     5.846E-02      1.807E-02
     AT ELEVATION (FT):        74.78          55.00
BENDING MOMENT (LB-FT):      3.426E+04     -4.126E+04
     AT ELEVATION (FT):        90.00          74.78

STAGE                  :     AFTER EXCAVATION TO EL.  72 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     9.350E-02      2.325E-02
     AT ELEVATION (FT):        74.78          51.00
BENDING MOMENT (LB-FT):      3.980E+04     -6.548E+04
     AT ELEVATION (FT):        90.00          74.78

STAGE                  :     AFTER ANCHOR INSTALLATION AT EL.  74 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     7.866E-02      1.349E-02
     AT ELEVATION (FT):       110.00          79.00
BENDING MOMENT (LB-FT):      3.186E+04     -2.593E+04
     AT ELEVATION (FT):        82.00          96.00

STAGE                  :     AFTER EXCAVATION TO EL.  64 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     7.541E-02      2.060E-02
     AT ELEVATION (FT):       110.00          83.00
BENDING MOMENT (LB-FT):      3.863E+04     -2.840E+04
     AT ELEVATION (FT):        82.00          68.00

STAGE                  :     AFTER ANCHOR INSTALLATION AT EL.  66 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     7.894E-02      2.837E-03
     AT ELEVATION (FT):       110.00          67.00
BENDING MOMENT (LB-FT):      3.652E+04     -2.616E+04
     AT ELEVATION (FT):        66.00          96.00

STAGE                  :     AFTER EXCAVATION TO EL.  58 (FT)

                              MAXIMUM       MINIMUM
DEFLECTION (FT)        :     7.930E-02      5.828E-03
     AT ELEVATION (FT):       110.00          73.00
BENDING MOMENT (LB-FT):      4.015E+04     -2.622E+04
     AT ELEVATION (FT):        66.00          96.00
```

Figure 3-22. Maxima summary for Cacoilo wall

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Appendix A
Guide for Data Input

A.1 Introduction

A.1.1 Source of input

Input data may be supplied from a predefined data file or from the user's keyboard during execution. When data are entered from the keyboard, prompts are provided to indicate the amount and character of data to be entered.

A.1.2 Data editing

Input data may be edited at any time until the construction sequence is initiated. After the construction sequence is complete, on-line editing is again available. However, the left-side profile will have been altered due to excavation resulting in inconsistencies with other data items.

A.1.3 Input data file generation

After data have been entered from the user's keyboard, the program writes all current input data to a temporary file in input file format. The temporary input file may be saved as a permanent file.

A.1.4 Sections of input

When data are entered from the user's keyboard, data sections may be entered in any order. When data are supplied from a predefined input file, sections must be entered in the following order:

a. Heading (Required).

b. Wall Segment Data (Required).

c. Anchor Data (Optional).

d. Soil Profile Data (Required).

e. Initial Water Data (Optional).

f. Surface Surcharge Data (Optional).

(1) Vertical line loads.

(2) Vertical uniform loads.

(3) Vertical strip loads.

(4) Vertical ramp loads.

(5) Vertical triangular loads.

(6) Vertical variable loads.

g. Excavation Data (Optional).

h. Wall Bottom Conditions (Optional).

i. Termination (Required).

A.1.5 Predefined data file

Data appearing in an input file must conform to the following:

a. Data items must be separated by one or more blanks. Comma separators are not permitted.

b. In the following input data descriptions, integer numbers are indicated by symbolic capitalized names beginning with the letters I,J,K,L,M,N. Integer data values may not contain a decimal point.

c. Real numbers are indicated by symbolic capitalized names beginning with the letters A through H and O through Z. Real number data values may be whole numbers (e.g., 1234 - no decimal), whole numbers with a fractional part (e.g., 123.456), or in exponential form (e.g., 1.234E05).

d. A line of input may contain both alphanumeric and numeric data items. Alphanumeric data items are enclosed in single quotes in the descriptions that follow.

e. A line of input may require a keyword. The acceptable abbreviation for a keyword is indicated by underlined capital letters; e.g., the acceptable abbreviation for the keyword <u>SU</u>rcharge is SU.

f. Data item enclosed in brackets [ ] may not be required. Data items enclosed in braces { } indicate that a special note follows.

g. Comment lines may be inserted in a data file by enclosing the line in parentheses. Comment lines are ignored by the program; e.g., (THIS LINE IS IGNORED).

h. The SOIL LAYER DATA section requires a descriptor {'side'} to indicate the side of the system to which the data apply. For symmetric effects ({'side'} = '<u>B</u>oth'), the data section is supplied only once and symmetric data are automatically applied to both sides. For unsymmetric conditions, the data for the '<u>R</u>ightside' (if required) must be entered first and immediately followed by the data for the '<u>L</u>eftside.'

A.2 Heading

This section consists of one to four lines.

a. Line contents.

\`heading\`

b. Definition.

\`heading\` = Any alphanumeric information up to 72 characters including embedded blanks. The first character in the line must be a single quote (\`).

A.3 Wall Segment Data

This section consists of 2 to 11 lines.

a. Line contents.

\`WALL\` ELSEG [WALLE WALLI]

b. Definitions.

\`WALL\` = Keyword.

ELSEG = Elevation (FT) at top of segment or elevation at bottom of last segment.

[WALLE] = Modulus of elasticity (PSI) of segment.

[WALLI] = Moment of inertia (IN^4) per foot of wall.

c. Discussion.

(1) The wall may be composed of one to ten prismatic segments.

(2) The segment data must begin with the topmost segment and proceed sequentially downward.

(3) The elevation on the last line is assumed to be the bottom of the wall (ELBOT in subsequent discussions).

A.4 Anchor Data

This section consists of zero or one to five lines; entire section may be omitted.

a. Line contents.

\`Anchor\` ELANCH FLOCK FYTENS ANC_EMOD ANC_AREA ANC_LENGTH ANC_SLOPE ANC_SPACE

b. Definitions.

\`Anchor\` = Keyword.

ELANCH = Elevation (FT) of anchor attachment at wall.

FLOCK = Anchor lock-off load (LBS).

FYTENS = Ultimate anchor force (LBS) in tension.

ANC_EMOD = Anchor modulus of elasticity (PSI).

ANC_AREA = Anchor cross-section area (IN^2).

ANC_LENGTH = Anchor effective length (FT).

ANC_SLOPE = Anchor slope (DEG).

ANC_SPACE = Horizontal spacing between adjacent anchors (FT).

c. Discussion.

(1) Anchors are assumed to extend to the right away from the wall and to slope downward at an angle ANC_SLOPE with the horizontal.

(2) Anchor forces (FLOCK and FYTENS) are assumed to act along the line of action of the anchor.

(3) Anchor properties are assumed to be total characteristics for a single anchor.

(4) The program evaluates anchor effects "per foot of wall."

(5) Anchor elevations must begin with the topmost anchor and proceed sequentially downward.

(6) Anchor elevations must be consistent with EXCAVATION DATA described in Section A.8.

A.5 Soil Profile Data

This section has two or more lines for each {'side'}.

a. Control: one line.

(1) Line contents.

'SOil' {'side'} {'Strengths'} NLAY

(2) Definitions.

'SOil' = Keyword.

{'side'} = 'Rightside', 'Leftside', or 'Both'.

{'Strengths'} = Keyword to indicate that internal friction, cohesion, and wall friction angle are provided.

NLAY = Number (1 to 11) of soil layers on this {'side'}.

b. Soil Layer Data: one line for each layer.

(1) Line contents.

ELLAYT GAMSAT GAMMST SU PHI {DELTA_A DELTA_P} [REFD_A REFD_P]

(2) Definitions.

ELLAYT = Elevation (FT) at intersection of top of layer with wall.

GAMSAT = Saturated unit weight (PCF) of soil (program subtracts unit weight of water from GAMSAT to obtain effective unit weight of submerged soil).

GAMMST = Moist unit weight (PCF) of unsubmerged soil.

SU = Undrained shear strength for cohesive soil.

PHI = Effective angle of internal friction (DEG) for drained conditions. PHI must be less than or equal to 45 degrees. Omit if SU is greater than zero.

DELTA_A = Angle of wall friction (DEG) to be applied to active pressure calculations. DELTA_A must be less than PHI. Omit if SU is greater than zero.

DELTA_P = Angle of wall friction (DEG) to be applied to passive pressure calculations. DELTA_P must be less than PHI. Omit if SU is greater than zero.

REFD_A = Reference displacement at active pressure limit; assumed to be default value if omitted.

REFD_P = Reference displacement at passive pressure limit; assumed to be default value if omitted. Omit if REFD_A is omitted.

(3) Discussion

(a) Layer top elevations must conform to:

ELLAYT(1) ≤ ELTOP

ELLAYT(i) < ELLAYT(i-1)

(b) At least one soil layer on each side of the wall is required. Up to eleven layers on each side are permitted.

(c) Soil layer data must commence with the topmost layer and proceed sequentially downward.

(d) The last layer on each side is assumed to extend downward ad infinitum.

(e) Both SU and PHI cannot be zero for a layer.

(f) Soil layer must be either purely cohesionless or purely cohesive. For a cohesionless soil, SU must be zero. For a cohesive layer, PHI must be zero.

(g) DELTA_A and DELTA_P must be positive and less than PHI for a cohesionless layer. Both must be zero for a cohesive soil.

(h) REFD_A and REFD_P must both be positive and nonzero.

(i) The program will generate identical soil layer data descriptions for both sides if {'side'} = 'Both'.

(j) If different profiles exist on each side of the wall, soil layer data must be entered twice, first for the 'Rightside' and immediately followed by data for the 'Leftside'.

(k) The soil profile for the entire right side must be provided. Profile data for the left side are assumed to commence at the level of the initial surface before the topmost anchor is installed. Left-side profile data are revised as each EXCAVATION ELEVATION is specified.

A.6 Initial Water Data

This section has zero or one line; entire section may be omitted.

a. Water Data: one line.

(1) Line contents.

['WATer' GAMWAT ELWATR ELWATL]

(2) Definitions.

'WATer Elevation' = Keywords.

GAMWAT = Water unit weight (PCF).

ELWATR = Elevation (FT) of water surface on right side.

ELWATL = Initial elevation (FT) of water surface on left side.

(3) Discussion.

(a) Effective soil unit weight for a drained submerged soil is calculated in the program by subtracting the unit weight of water from the saturated unit weight of soil.

(b) Initial water elevations are applied to the initial soil profile. The water level on the right side is unaltered during the solution process. The water elevation on the left side may be altered by Excavation Data.

A.7 Right-Side Surface Surcharge Data

a. Line Loads: zero or one line.

(1) Line contents.

['Vertical Line' NVL DL(1) QL(1) ... DL(NVL) QL(NVL)]

(2) Definitions.

`Vertical Line` = Keywords.

NVL = Number (1 to 5) of line loads on this {`side`}.

DL(i) = Distance (FT) from wall to point of application of i^{th} line load.

QL(i) = Magnitude (PLF) of i^{th} line load

(3) Discussion.

(a) Up to five line loads may be applied to the surface on the right side.

(b) DL(i) must be greater than zero.

(c) QL(i) must be greater than zero (i.e., upward loads are not permitted).

b. Uniform Load: zero or one line.

(1) Line contents.

[`Vertical Uniform QUR]

(2) Definitions.

`Vertical Uniform` = Keywords.

QUR = Magnitude (PSF) of uniform surcharge on right-side surface.

(3) Discussion.

(a) A uniform surcharge extends to infinity away from the wall.

(b) QUR must be greater than or equal to zero (i.e., upward loads are not permitted).

c. Strip Loads: zero or one or more lines.

(1) Line 1 contents.

[`Vertical Strip` NVS DS1(1) DS2(1) QS(1)]

(2) Lines 2 through NVS contents.

$$\begin{bmatrix} DS1(2) & DS2(2) & QS(2) \\ \vdots & \vdots & \vdots \\ DS1(NVS) & DS2(NVS) & QS(NVS) \end{bmatrix}$$

(3) Definitions.

`Vertical Strip` = Keywords.

NVS = Number (1 to 5) of strip loads on this {`side`}.

DS1(i) = Distance (FT) to start of strip load.

DS2(i) = Distance (FT) to end of strip load.

QS(i) = Magnitude (PSF) of uniform strip load.

(4) Discussion.

(a) A maximum of five strip loads may be applied to the right side.

(b) QS(i) must be greater than or equal to zero; i.e., upward loads are not permitted).

(c) Distances must conform to:

$DS1(i) \geq$ Zero.

$DS2(i) > DS1(i)$

d. Ramp Loads: zero or one line.

(1) Line contents.

['Vertical Ramp' DR1 DR2 QR]

(2) Definitions.

'Vertical Ramp' = Keywords.

DR1 = Distance (FT) to start of ramp load.

DR2 = Distance (FT) to end of ramp portion.

QR = Magnitude (PSF) of uniform portion of ramp load.

(3) Discussion.

(a) A ramp load is interpreted as acting on the horizontal projection of a sloping surface.

(b) Distances must conform to:

$DR1 \geq$ Zero.

$DR2 \geq DR1$.

(c) QR must be greater than or equal to zero (i.e., upward load is not permitted).

e. Triangular Loads: zero, one or more lines.

(1) Line 1 contents.

['Vertical Triangular' NVT DT1(1) DT2(1) DT3(1) QT(1)]

(2) Lines 2 through NVT contents.

$$\begin{bmatrix} DT1(2) & DT2(2) & DT3(2) & QT(2) \\ \vdots & \vdots & \vdots & \vdots \\ DT1(NVT) & DT2(NVT) & DT3(NVT) & QT(NVT) \end{bmatrix}$$

(3) Definitions.

`Vertical Triangular` = Keywords.

NVT = Number (1 to 5) of triangular loads on the right side.

DT1(i) = Distance (FT) to beginning of i^{th} triangular load.

DT2(i) = Distance (FT) to peak of i^{th} triangular load.

DT3(i) = Distance (FT) to end of i^{th} triangular load.

QT(i) = Magnitude (PSF) at peak of i^{th} triangular load.

(4) Discussion.

(a) A maximum of five triangular loads may be applied to the surface on the right side.

(b) Distances must conform to:

DT1(i) $\geq$ Zero.

DT2(i) > DT1(i) if DT3(i) = DT2(i).

DT3(i) > DT2(i) if DT2(i) = DT1(i).

DT3(i) > DT1(i).

(c) QT(i) must be greater than or equal to zero (i.e., upward load is not permitted).

f. Variable Distributed Loads: zero or one or more lines.

(1) Line 1 contents.

[`Vertical Variable` NVV DV(1) QV(1) DV(2) QV(2)]

(2) Lines 2 through (NVV) contents:

$$\begin{bmatrix} DV(3) & QV(3) \\ \vdots & \vdots \\ DV(NVV) & QV(NVV) \end{bmatrix}$$

(3) Definitions.

`Vertical Variable` = Keywords.

NVV = Number (2 to 11) of points on distribution on this {`side`}.

DV(i) = Distance (FT) to i^{th} point on distribution.

QV(i) = Magnitude (PSF) of distributed load at i^{th} point.

(4) Discussion.

(a) At least two points are required on a distribution. Up to eleven points are permitted.

(b) The load is assumed to vary linearly between successive points.

(c) Distances must conform to:

$DV(1) \geq$ Zero.

$DV(i) > DV(i-1)$

(d) QV(i) must be greater than or equal to zero (i.e., upward loads are not permitted).

A.8 Excavation Data

This section consists of zero or one line; omit if number of anchors is zero.

a. Line 1 contents.

['Excavation']

(1) Definition.

'Excavation' = Keyword

b. Lines 2 to NANCHS lines contents.

EXCAV_EL(1) [EXCAV_WATEL(1)]

⋮ ⋮

EXCAV_EL(NANCHS) [EXCAV_WATEL(NANCHS)]

(1) Definitions.

EXCAV_EL(I) = Elevation (FT) of left-side soil surface after excavation

[EXCAV_WATEL(I)] = Elevation (FT) of left-side water surface after excavation; omit if Initial Water Data are omitted

c. Discussion.

(1) The number of excavation (and left-side water) elevations must be the same as the number (NANCHS) of anchors.

(2) Up to five excavation (and left-side water) elevations may be specified.

(3) Elevations must conform to:

$$\text{EXCAV}(i) < \text{ELANCH}(i)$$

$$\text{EXCAV}(i) \leq \text{EXCAV}(i\text{-}1)$$

$$\text{EXCAV\_WATEL}(1) \leq \text{Initial ELWATL}$$

$$\text{EXCAV\_WATEL}(i) \leq \text{EXCAV\_WATEL}(i\text{-}1)$$

A.9 Wall Bottom Conditions

This section consists of zero or one line.

a. Line contents.

`Bottom` {`conditions`}

b. Definitions.

`Bottom` = Keyword

`conditions` = `FRee` if lateral and rotational displacements are free to occur

= `FIxed` if both lateral and rotational displacements are zero

= `Pinned` if lateral displacement is zero and rotational displacement is free to occur

c. Discussion.

(1) If the **WALL BOTTOM CONDITIONS** section is omitted a `FRee` condition is assumed.

A.10 Termination

This section consists of one line.

a. Line contents.

`Finished`

Appendix B
Abbreviated Input Guide

The input data consist of the following sections:

a. Heading: One to four lines.

'heading'
['heading']
['heading']
['heading']

b. Wall Segment Data: Two to eleven lines.

'WALl' ELSEG [WALLE WALLI WALLA]

c. Anchor Data: Zero or one to five lines.

'Anchor' ELANCH FLOCK FYTENS ANC_EMOD ANC_AREA ANC_LENGTH ANC_SLOPE ANC_SPACE

d. Soil Profile Data: Two or more lines.

(1) Control -- One line:

'SOil' {'side'} 'Strengths' NLAY

(2) Layer Data -- NLAY lines:

ELLAYT GAMSAT GAMMST SU PHI DELTA_A DELTA_P [REFD_A REFD_P]

e. Initial Water Data -- Zero or one line.

['WATer' GAMWAT ELWATR ELWATL]

f. Right-Side Surface Surcharge Data.

(1) Line Loads -- Zero or one or two lines.

['Vertical Line' NVL DL(1) QL(1) ··· DL(NVL) QL(NVL)]

(2) Uniform Loads -- Zero or one line.

['Vertical Uniform' QUR]

(3) Strip Loads -- Zero or one or more lines.

(a) Line 1:

['Vertical Strip' NVS DS1(1) DS2(1) QS(1)]

(b) Lines 2 to NVS:

$$\begin{bmatrix} \text{DS1(2)} & \text{DS2(2)} & \text{QS(2)} \\ \vdots & \vdots & \vdots \\ \text{DS1(NVS)} & \text{DS2(NVS)} & \text{QS(NVS)} \end{bmatrix}$$

(4) Ramp Loads -- Zero or one or two lines.

['Vertical Ramp' DR1 DR2 QR]

(5) Triangular Loads -- Zero or one or more lines.

(a) Line 1:

['Vertical Triangular' NVT DT1(1) DT2(1) DT3(1) QT(1)]

(b) Lines 2 to NVT:

$$\begin{bmatrix} \text{DT1(2)} & \text{DT2(2)} & \text{DT3(2)} & \text{QT(2)} \\ \vdots & \vdots & \vdots & \vdots \\ \text{DT1(NVT)} & \text{DT2(NVT)} & \text{DT3(NVT)} & \text{QT(NVT)} \end{bmatrix}$$

(6) Variable Loads -- Zero or one or more lines.

(a) Line 1:

['Vertical Variable' NVV DV(1) QV(1) DV(2) QV(2)]

(b) Lines 2 to NVV:

$$\begin{bmatrix} \text{DV(3)} & \text{QV(3)} \\ \vdots & \vdots \\ \text{DV(NVV)} & \text{QV(NVV)} \end{bmatrix}$$

g. Excavation Data -- Zero or two or more lines.

(1) Line 1 contents:

'Excavation'

(2) Lines 2 to NANCHS contents:

$$\begin{bmatrix} \text{EXCAV\_EL(1)} & [\text{EXCAV\_WATEL(1)}] \\ \vdots & \vdots \\ \text{EXCAV\_EL(NANCHS)} & [\text{EXCAV\_WATEL(NANCHS)}] \end{bmatrix}$$

h. Wall Bottom Conditions -- Zero or one line

(1) Line contents:

$$\left[\text{`}\underline{\text{B}}\text{ottom`} \quad \left\{\begin{array}{l} \text{`}\underline{\text{FR}}\text{ee`} \\ \text{`}\underline{\text{FI}}\text{xed`} \\ \text{`}\underline{\text{P}}\text{inned`}\end{array}\right\}\right]$$

i. Termination -- One line.

`}\underline{\text{F}}\text{inished`

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Technical Report K-80-2	Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges	Jan 1980
Instruction Report K-80-1	User's Guide: Computer Program for Design/Review of Curvi-linear Conduits/Culveris (CURCON)	Feb 1980
Instruction Report K-80-3	A Three-Dimensional Finite Element Data Edit Program	Mar 1980
Instruction Report K-80-4	A Three-Dimensional Stability Analysis/Design Program (3DSAD)	
	Report 1: General Geometry Module	Jun 1980
	Report 3: General Analysis Module (CGAM)	Jun 1982
	Report 4: Special-Purpose Modules for Dams (CDAMS)	Aug 1983
Instruction Report K-80-6	Basic User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Instruction Report K-80-7	User's Reference Manual: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Technical Report K-80-4	Documentation of Finite Element Analyses	
	Report 1: Longview Outlet Works Conduit	Dec 1980
	Report 2: Anchored Wall Monolith, Bay Springs Lock	Dec 1980
Technical Report K-80-5	Basic Pile Group Behavior	Dec 1980
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(Continued)

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Technical Report ITL-87-2	A Case Committee Study of Finite Element Analysis of Concrete Flat Slabs	Jan 1987
Instruction Report ITL-87-2 (Revised)	User's Guide for Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-89	Mar 1992
Instruction Report ITL-87-1	User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame Structures (CUFRAM)	Apr 1987
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(Continued)

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	Report 4: Alternate Configuration Miter Gate Finite Element Studies-Closed Sections	
	Report 5: Alternate Configuration Miter Gate Finite Element Studies-Additional Closed Sections	
	Report 6: Elastic Buckling of Girders in Horizontally Framed Miter Gates	
	Report 7: Application and Summary	
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(Continued)

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(Continued)

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(Continued)

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(Continued)

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(Concluded)

	Title	Page
Technical Report ITL-99-1	Development of an Improved Numerical Model for Concrete-to-Soil Interfaces in Soil-Structure Interaction Analyses Report 1: Preliminary Study Report 2: Final Study	 Jan 1999 Aug 2000
Technical Report ITL-99-5	River Replacement Analysis	Dec 1999
ERDC/ITL TR-00-1	Evaluation and Comparison of Stability Analysis and Uplift Criteria for Concrete Gravity Dams by Three Federal Agencies	Jan 2000
ERDC/ITL TR-00-2	Reliability and Stability Assessment of Concrete Gravity Structures (RCSLIDE): User's Guide	Jul 2000
ERDC/ITL TR-00-5	Theoretical Manual for Pile Foundations	Nov 2000
ERDC/ITL TR-01-2	SOILSTRUCT-ALPHA for Personal Computers Report 1: Visual Modeler	Dec 2001
ERDC/ITL TR-01-3	Finite Element Modeling of Cooling Coil Effects in Mass Concrete Systems	Aug 2001
ERDC/ITL TR-01-4	Investigation of Wall Friction, Surcharge Loads, and Moment Reduction Curves for Anchored Sheet-Pile Walls	Sep 2001
ERDC/ITL TR-01-7	Smeared and Discrete Crack Evaluations of a Lock Exhibiting Earth Pressure-Induced Cracking	Dec 2001
ERDC/ITL SR-03-1	User's Guide: Computer Program for Simulation of Construction Sequence for Stiff Wall Systems with Multiple Levels of Anchors (CMULTIANC)	Aug 2003

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14. ABSTRACT
This report describes the PC-based computer program CMULTIANC, used to evaluate the effects of staged construction activities (i.e., excavation and tieback post-tensioning) on wall and soil behavior. The CMULTIANC simplified construction sequencing analysis is applicable to stiff walls with a single row or multiple rows of post-tensioned tieback anchors. Top-down construction is assumed in this analysis procedure.

The retaining wall system is modeled using beam on inelastic foundation methods with elastoplastic soil-pressure deformation curves (R-y curves) used to represent the soil behavior. The R-y curves are developed within the CMULTIANC program in accordance with the reference deflection method. The retaining wall is analyzed on a per-unit length run of wall basis. One-dimensional finite elements are used to model the retaining wall with closely spaced inelastic concentrated springs to represent soil-to-structure interactions on both sides of the wall. Discrete concentrated, elastoplastic springs are used to represent the anchors.

For each level of excavation (associated with a particular tieback installation) CMULTIANC performs three sequential analyses: (a) staged excavation analysis (to the excavation level needed for anchor installation) to capture soil loading effects, (b) R-y curve shifting to capture plastic soil movement effects, and (c) tieback installation analysis to capture tieback anchor prestressing effects. R-y curves are shifted to capture the plastic movement that takes place in the soils as the wall displaces toward the excavation for those
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15. SUBJECT TERMS

Construction sequencing	Prestressed anchors	Soil springs
Ground anchor wall	Reference deflection method	Tieback wall

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conditions where actual wall computed displacements exceed active computed displacements. R-y curve shifting is necessary to properly capture soil reloading effects as tieback anchors are post-tensioned and the wall is pulled back into the retained soil.